EXTENT ASSESSMENT OF BLAST-INDUCED FRACTURES USING A STOCHASTIC APPROACH

THESIS PROPOSAL

Proposal for Thesis Research in partial fulfillment of the requirements for the degree of Master of Science in the College of Engineering at the University of Kentucky

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2022

Abstract

Despite the development and implementation of new equipment in the underground metallic mining industry worldwide, such as mechanical rock cutting systems, they are still in field trial testing, therefore blasting remains as the predominant rock excavation method. Underground blasting has been proven to be an efficient method in terms of advance rate, when it is done properly, guaranteeing a minimum overbreak and stability of the remaining excavated rock. This is done as a result of blasting techniques applied in the face perimeter. One of the most widely used techniques is smooth blasting. The underlying principle of this technique is directly related to the coupling ratio, which is the ratio between the borehole and the charge diameter, and the damage radius produced by the explosives in the boundary. Several studies are available in the literature to estimate the radius of the crushed zone, deterministically. In this research, a probabilistic approach will be developed based on four blast-damage models. This is due to the initiation and propagation of cracks having a probabilistic nature, and neither the initial state of the rock nor the explosion load could be expressed in a fully deterministic way. Therefore, after generating random values for involved parameters, including explosive density, detonation velocity, Young's modulus, Poisson's ratio, uniaxial compressive strength, the Monte-Carlo sampling method will be adopted to calculate the exceeding probability of the crushed zone radius from desired values. The results will be compared against a real blast performed in a concrete sample at the University of Kentucky Explosives Research Team facilities in Georgetown, KY. The results from this study, compared to the deterministic models, will provide advantages in that they are not only limited to a certain value for the crushed zone radius and show the probability of exceedance for any required radius.

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1. Introduction

Falls of ground[1] in underground mining works are one of the leading causes of injuries and fatalities for mine workers in the US. Underground mining has one of the highest fatal injury rates in the American industry —more than five times the national average compared to other industries [1]. Between 1990 and 2020, nearly 40% of all underground fatalities were attributed to roof, rib, and face falls [2], as shown in Figure 1.1.

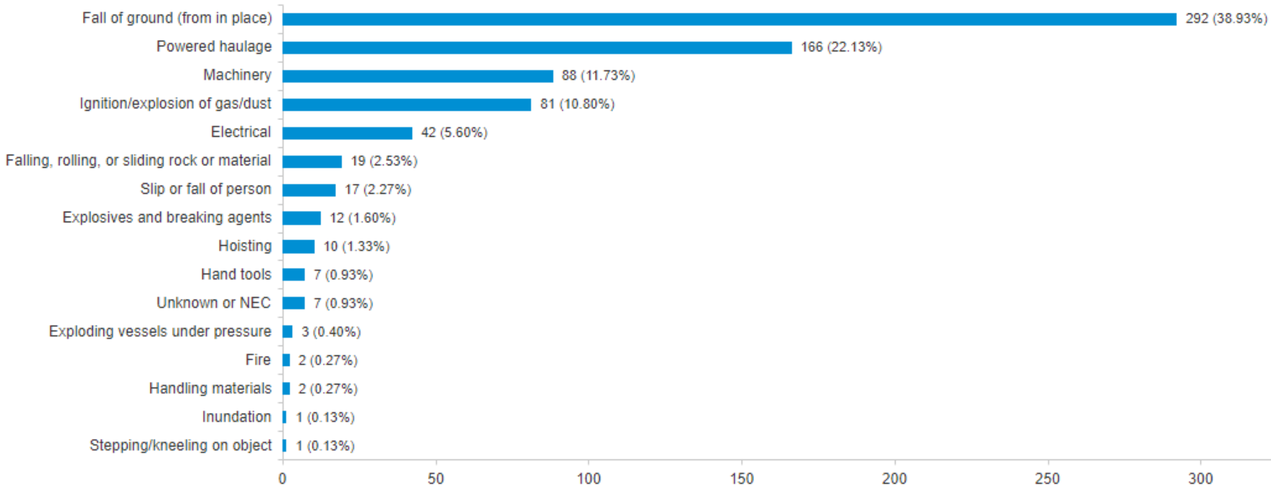


Fig. 1.1 Number and percentage of occupational fatalities by accident class at underground mining locations, coal operators, metal operators, nonmetal operators, stone operators, sand & gravel operators, coal contractors, noncoal contractors in the US, 1990 – 2020 (n=750)

While underground mechanical rock cutting systems are still in field trial period around the world [3], in the standard mining cycle, right after drilling, blasting is the preferred unit operation when the rock mass has medium to high UCS (uniaxial compressive strength). After a rock blasting operation is completed, the remaining rock mass is part of a structure that is expected to remain stable, sometimes requiring additional rock support systems such as wire mesh, shotcrete or steel arches. The strength and stability of the rock mass surrounding large, permanent, underground openings are of significant importance to prevent rockfalls that could injure people and damage equipment.

Rock blasting techniques in underground metal/nonmetal mines need to be optimized to minimize the extent of loose and/or damaged rock surrounding blasted openings, thereby reducing mine worker exposure to ground fall hazards. Optimized blasting techniques are primarily dependent on

[1] "Fall of ground (from in place)" includes MSHA's Accident/Injury/Illness classifications for "Fall of face, rib, pillar, side, or highwall (from in place)" and "Fall of roof, back, or brow (from in place)." Excludes office employees. Source: MSHA

the blast pattern, and the type and quantity of explosives used at the perimeter of the excavation. In most underground mines, loose ground are located on the roof and it is removed by hand scaling or mechanical scaling, being the latter the preferred method from a safety perspective. Although scaling reduces the risks of rockfall injuries, the personnel responsible for scaling can be at risk when performing this task. An appropriate blasting technique to minimize the damage done to the loose remaining rock is overbreak control. The less competent the rock mass is, the more care it has to be taken to prevent the structure (the remaining rock) from getting damaged. When control of the perimeter is desired, blasting methods lowering the borehole charge concentration adjacent to the final perimeter are usually employed. All methods of cautious blasting have one common objective: to better distribute the explosive energy which is transmitted into the rock mass as a result of the detonation reaction. Furthermore, an optimum overbreak control avoids a higher dilution in benefit of the ore recovery from a mine-to-mill standpoint. Most of these methods have been developed in the field, mainly by trial and error. The most widely used technique in underground mining is called smooth blasting, sometimes referred to as post splitting, contour blasting, perimeter blasting or sculpture blasting [4]. The conceptual difference of two blasts using smooth blasting and not using it is shown in Figures 1.2 and 1.3.

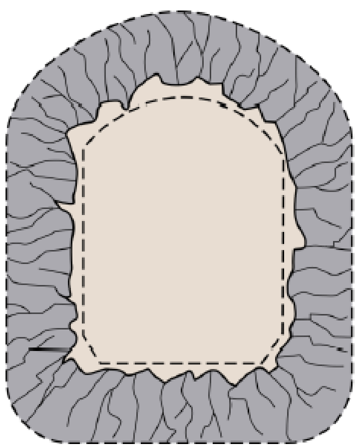


Fig. 1.2 Crack zone with conventional blasting (adapted from [5]*)*

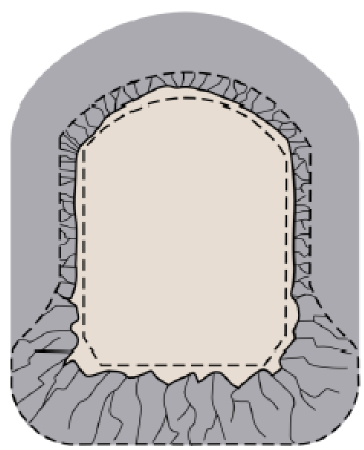


Fig. 1.3 Crack zone with smooth blasting (adapted from [5]*)*

Smooth blasting is a method where the row of holes adjacent to the planned contour is fired at the end of the round, with a light charge per hole, with a small spacing, and usually with a Spacing to Burden ratio of 0.8. For best results in smooth blasting, the charges in the contour should be initiated simultaneously, so that they can produce the expected effects [6]. Moreover, the simultaneous firing of a large number of contour holes in an underground blast would create large ground vibrations.

Therefore, the contour holes are often distributed over several time intervals; and because the contour rows are fired at the end of a long-duration tunnel blast with many time delays, the scatter in the timing of these long delay detonators is considerable [6]. Results from smooth blasting in an underground polymetallic mine in Peru are observed in Figure 1.4.

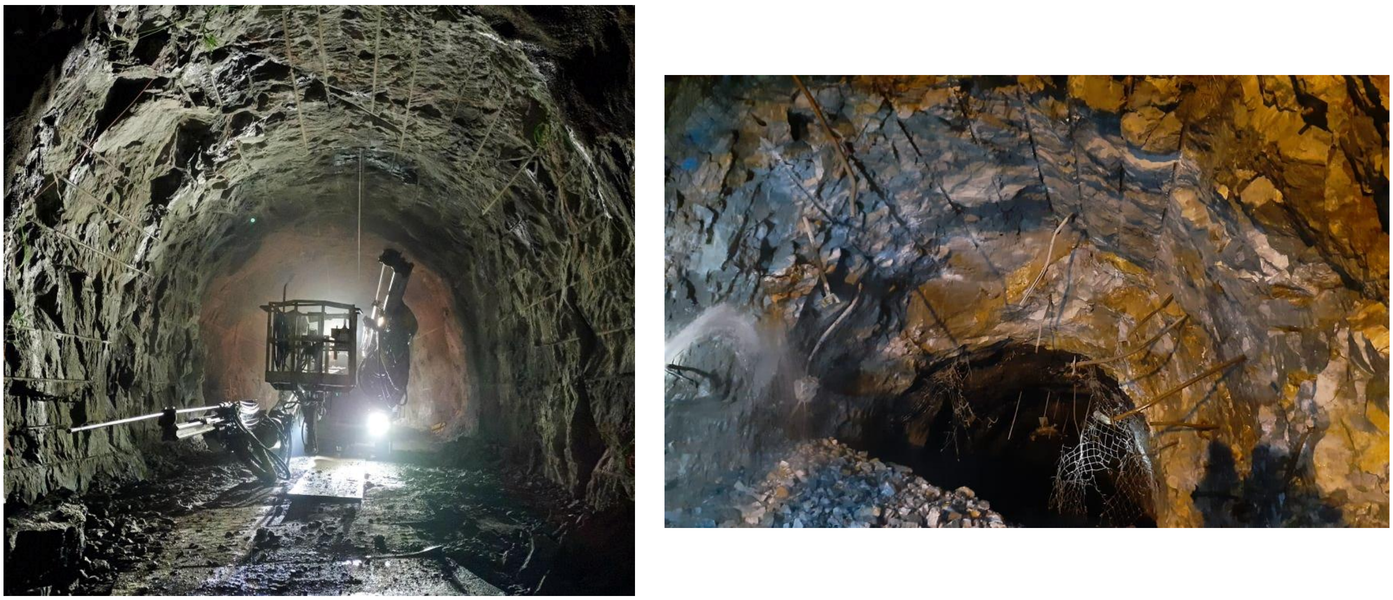


Fig. 1.4 Borehole marks on the underground perimeter of a stope after smooth blasting was applied (original pictures from an UG mine in Peru)

There are no less than 18 methods that have been proposed to predict damage due to rock blasting [7]. The proposed research in this thesis will use four of the most representative methodologies to assess the fracture extension around a single borehole to implement a probabilistic approach to the fracture extension problem. Then the results from the modified models will be compared against an actual field test in a concrete block test.

2. Literature review

The detonation of the explosive will fill the blasthole with gaseous detonation products at a very high pressure and temperature. This pressure is transmitted instantly to the surrounding surface of the blasthole, generating a radial compressive stress higher than the strength of the rock (Fig. 2.1).

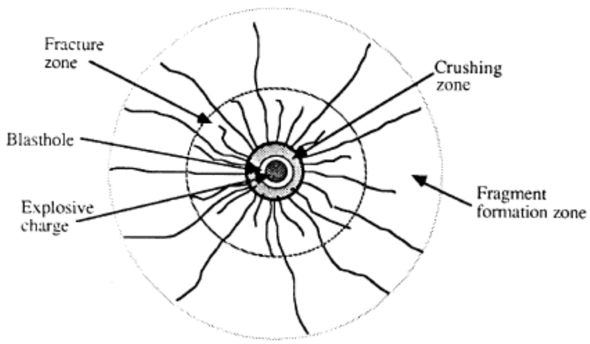
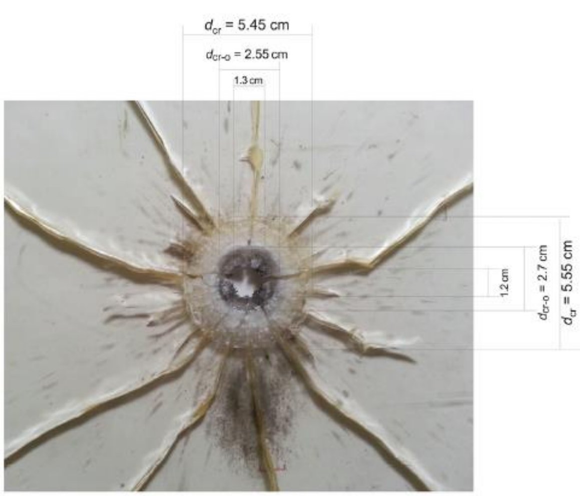


Fig. 2.1 Schematic illustration of processes taking place in the rock around a single borehole (Adapted from [8]*)*

Around the borehole, the process yields a series of microcracking due to the differential compression of the particles and matrix of the rock, and other forms of plastic deformation [8]. A single-hole detonation experiment in Plexiglas by Johansson and Persson [9] clearly demonstrated that (1) the original borehole expanded, (2) a fractured zone appeared surrounding the borehole, and (3) outside the fractured zone was a shock or stress wave. Since the 1970s, a significative number of blast trials have confirmed these observations. Figure 2.2 shows the blasting results from a polymethyl methacrylate (PMMA) plate. The plate has a size of 30 cm × 30 cm × 1 cm. At the center of the plate, there was a hole in which a detonator with a diameter of 7 mm equal to the diameter of the hole was inserted as the explosive charge.



(a)

(b)

Fig. 2.2 Crushed zone and cracks in a PMMA plate by full charge: the sizes of the PMMA plate were 30 cm long, 30 cm wide, and 1 cm thick (the pictures show only part of the plate). The diameter of the blast hole was 7 mm. The charge was an electric detonator with a diameter of 7 mm. The two pictures show the same blast in the same plate. (a) Fracture pattern with sizes; (b) part of fracture system. (Adapted from [10]*)*

Four of the most characteristic blast damage models are briefly included in this document. They provide either damage limits or expected PPV values associated with measured damage surrounding the charged borehole. The main criterion to choose these methodologies was their adaptability to apply a stochastic behavior to their component variables. Nonetheless, in the thesis, a comprehensive review of other existing methodologies will be included.

2.1 The modified Ash Pressure-Based blast damage model

The blast damage distance by the Modified Ash Pressure model for a decoupled or fully coupled charge is developed by adding scaling by the wall pressure to explosion pressure ratio to the Modified Ash Energy model as shown in equation 2.1:

$$R_d = 12.5 \times D_e \times \sqrt{RBS_e \times \frac{2.65}{SG_r} \times \left(\frac{D_e}{D_h}\right)} \quad (2.1)$$

where:

R_d : blast damage distance (m)
D_e : explosive charge diameter (m)
D_h : blasthole diameter (m)
RBS_e : explosive relative bulk strength
SG_r : rock specific gravity
2.65 : reference rock specific gravity

In Equation 2.1, the variables susceptible for randomization are the RBS_e, SG_r.

2.2 Etkin Energy-based blast damage model

Etkin proposed an equation that replaces the rock constant with a powder factor (PF_A). The form of the Etkin blast damage distance model is shown in equation 2.2:

$$R_d = 12.5 \times D_e \times \sqrt{0.4\pi \times \frac{SG_e \times RWS_e}{PF_A}} \quad (2.2)$$

where:

R_d : blast damage distance (m)
D_e : explosive charge diameter (m)

SG_e : explosive specific gravity
RWS_e : explosive relative weight strength
PF_A : powder factor (kg/m^3)

In Equation 2.2, the variables that will be randomized are the RWS_e, SG_e, PF_A.

2.3 Szuladzinski model

Szuladzinski [11] models the crushing and cracking in the proximity of a blasthole from transient dynamic analysis. The rock is modeled as an elastic body with an implied crushing capability and a definite cracking strength. The relationship proposed to estimate the radius of crushing r_c (mm) is shown in equation 2.3:

$$r_c = \sqrt{\frac{2r_o^2 \times \rho_o \times Q_{ef}}{F_c^{'}}} \tag{2.3}$$

where:

r_o : borehole radius (mm)
ρ_0 : explosive density (g/cm^3)

Q_{ef} : effective energy of the explosive (N$\times$ mm/g). Assumed to be 2/3 of the heat of complete reaction.

$F_c^{'}$: confined dynamic compressive strength of the rock material (MPa). Assumed to be approximately eight times the value of unconfined static compressive strength, σ_c (MPa).

In Equation 2.3, the variables undergoing a randomization process are the Q_{ef}, $F_c^{'}$, ρ_0

2.4 Holmberg-Persson model

The Holmberg-Persson perimeter blast design approach has been used widespread since its introduction in 1978 [6]. However, a recently discovered mistake in the equation development has raised questions regarding the whole procedure. Although there exists the mathematic mistake in the Holmberg-Persson approach that could cause an error, one still cannot deny the fact that many successful applications of this approach can be found in practice. The reason for this could be that the underestimate of the PPV caused by the mathematic mistake introduced partly offsets the overestimate of the PPV introduced by the method itself [12].

The Holmberg and Persson expression is an integration over the charge length for a charge concentration identified over z initial (z_i) to z final (z_f) as shown in equation 2.4:

$$PPV = K\left\{ q\int_{z_i}^{z_f} \frac{dz}{\left[(r-r_o)^2 + (z-z_0)^2 \right]^{\beta/2\alpha}} \right\}^{\alpha} \quad (2.4)$$

where:

PPV : peak particle velocity
K,α,β : constants
q : charge concentration (kg/m)
r : element radial location (m)
z : element location along the charge (m)
r_o : radial measure point (m)
z_o : longitudinal measure point (m)

The randomization of the extension fracture models will include the analysis of the distribution of the parameters susceptible to include in the models in a stochastic manner.

3. Proposal for thesis research

3.1 Project objective

The objective of this research is to assess the fracture extensions due to blasting in a twofold procedure (deterministic and probabilistic) using four blast-damage models and compare those results against a real blast test.

3.2 Scope of Research

In scope:

a. The explosives to use are boosters and they will work in conjunction with an electronic detonator for better performance or with a nonel detonator.
b. The research will be carried out in a concrete block at UKERT facilities in Georgetown.
c. All the resources (equipment, personnel) will be provided by UKERT.

Out of scope:

a. The blasting behavior will not be modelled per se, but the extension of the fractures resulting from it.

3.3 Work Plan

This thesis focuses on the probability analysis of explosion and crushed zone growth due to blasting. Bearing this in mind, a deterministic model in which we can express the crushed zone radius by a closed-form relation needs to be done first. Then, defining the involved parameters as random variables and their probability distributions, the problem can be transferred from a deterministic to a probabilistic state, and it can be established as a reliability problem. This can be summarized in Fig. 3.1.

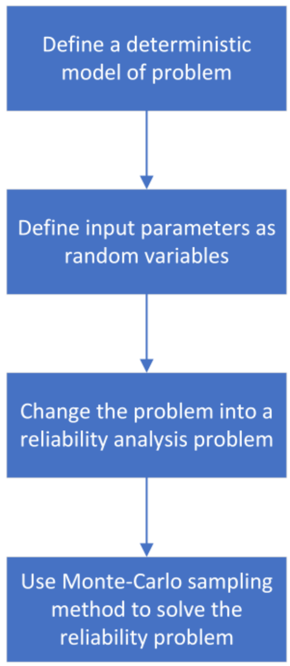


Fig. 3.1 Probabilistic modeling process

3.3.1 Task 1: Literature review

A comprehensive review of the existing blast-damage models and case studies will be carried out in this chapter.

3.3.2 Task 2: Probabilistic and deterministic analysis

Out of the reviewed blast-damage models, four will be selected to perform both a deterministic and probabilistic analysis. The Monte-Carlo algorithm will be applied as indicated in Figure 3.2:

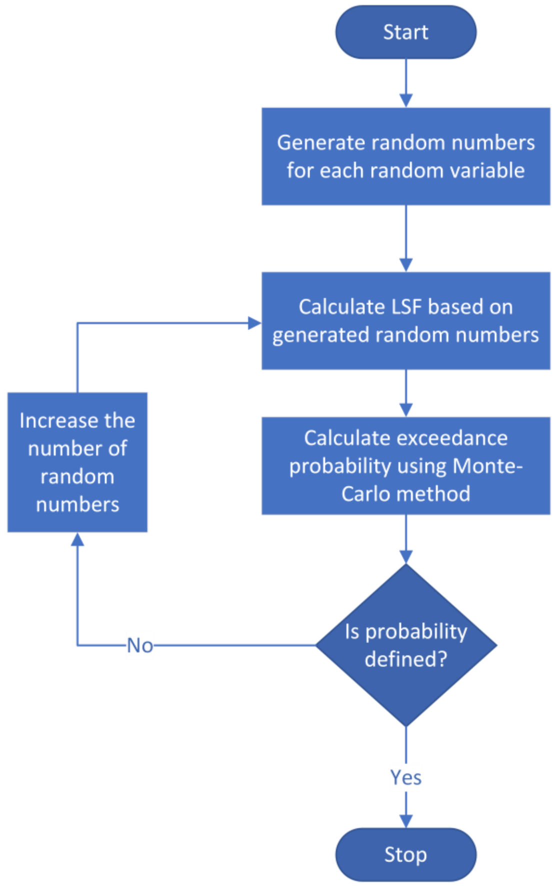
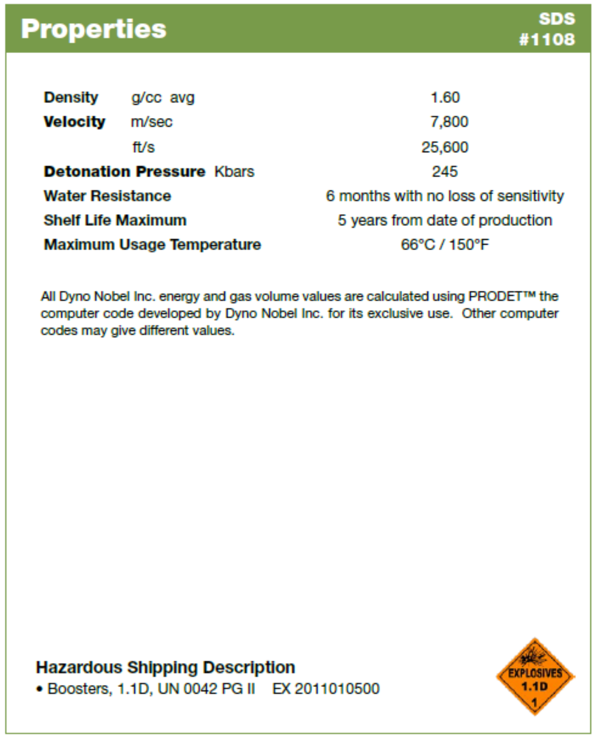


Fig. 3.2 Monte-Carlo algorithm for reliability analysis

3.3.3 Task 3: Field blast test on concrete block

At the UKERT facilities in Georgetown, a blast test will be conducted on a concrete block using booster /stinger from Dyno Nobel. The explosive properties are shown in Figure 3.3.



Properties SDS #1108

Density	g/cc avg	1.60
Velocity	m/sec	7,800
	ft/s	25,600
Detonation Pressure	Kbars	245
Water Resistance		6 months with no loss of sensitivity
Shelf Life Maximum		5 years from date of production
Maximum Usage Temperature		66°C / 150°F

All Dyno Nobel Inc. energy and gas volume values are calculated using PRODET™ the computer code developed by Dyno Nobel Inc. for its exclusive use. Other computer codes may give different values.

Hazardous Shipping Description

• Boosters, 1.1D, UN 0042 PG II EX 2011010500

Fig. 3.3 Properties of the explosive to be used in the field test (Dyno Nobel)

3.4 Timeline

A Gannt chart of the project tasks is shown in Table 3.1. The main task will be number 3 due to the risks associated with explosives. Safety measures will be adopted properly as deemed necessary.

Table 3.1 Gannt chart of the project

							Ene		Feb				Mar				Apr				May					Jun				Jul				Aug					Sep				Oct					Nov				Dic			
Id	**Milestones**	**Owner**	**Start**	**End**	**Dur. (days)**	**Status (%)**	24	31	7	14	21	28	7	14	21	28	4	11	18	25	2	9	16	23	30	6	13	20	27	4	11	18	25	1	8	15	22	29	5	12	19	26	3	10	17	24	31	7	14	21	28	5	12	19	26
1	Task 1: Literature Review chapter	LV	24-01	28-02	36	30%																																											
2	Task 2: Prob. and deterministic analysis of 04 blast-damage	LV	07-03	16-05	71	0%																																											
3	Task 3: Field blast test	LV / JC	22-08	03-10	43	0%																		Internship																														
4	Task 4: Compilation and completion	LV	10-10	05-12	57	0%																																											

3.5 Budget

All the cost incurred in the present thesis will be covered by the University of Kentucky Explosives Research Team (UKERT). An estimated breakdown of the costs is shown in Table 3.2.

Table 3.2 Cost estimation for the scope set in the thesis project

Concept	Cost	Comments
Labor	0.00	Included in monthly stipend
Software	0.00	Covered by UK IT if using Matlab®
Fuel	100.00	Transportation to Georgetown facilities
Total	$100.00	

3.6 Contribution

The results from this study, compared to the deterministic models, will provide an insight in that they are not only circumscribed to a certain value for the crushed zone radius and show the probability of overrunning for any required radius.

4. References

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