Finite element simulations of mine blast effects - a convergence study using GRALE2D

Lars Olovsson, Tommie Sundel,
Anders Tjernberg, Bo Johansson

FOI-R-- 1703 --SE
ISSN 1650-1942

Weapons and Protection
Technical report

August 2005

FOI
Defence Research Agency
Weapons and Protection
SE-147 25 Tumba

Phone: +46 8 555 030 00
Fax: +46 8 555 031 00

www.foi.se

Finite element simulations of mine blast effects - a convergence study using GRALE2D

FOI-R--1703--SE
ISSN 1650-1942

Weapons and Protection
Technical report

August 2005

Issuing organization
FOI – Swedish Defence Research Agency

Weapons and Protection
SE-147 25 Tumba

Report number, ISRN
FOI-R--1703--SE

Report type
Technical report

Research area code
5. Strike and protection

Month year
August 2005

Project no.
E2036

Sub area code
51 Weapons and Protection

Sub area code 2

Author/s (editor/s)
Lars Olovsson
Tommie Sundel
Anders Tjernberg
Bo Johansson

Project manager
Bo Johansson

Approved by

Sponsoring agency
Swedish Armed Forces

Scientifically and technically responsible

Report title

Finite element simulations of mine blast effects - a convergence study using GRALE2D

Abstract

This work is a convergence study with the objective to work out guidelines for the in-house finite element code GRALE2D in axi-symmertrical mine blast simulations. The reflected pressure pulse against a rigid flat surface at different charge sizes, at stand-off distance 50*cm*, has been analysed for both surface laid and buried mines. Geometries and dimensions were chosen as to resemble the situation of a vehicle exposed to a mine blast.

The results indicate certain problems at obtaining converged results for local pressure peaks near the axis of revolution. This is especially the case in situations where the mine is covered by a layer of soil. However, global results and impulse intensities generally converge quite well.

The report is concluded with some suggestions regarding element size at different charge sizes.

Keywords
GRALE2D, blast, convergence study

Further bibliographic information

Language English

ISSN 1650-1942

Pages 36 p.

Price acc. to pricelist

Utgivare
FOI - Totalförsvarets forskningsinstitut
Vapen och skydd
147 25 Tumba

Rapportnummer, ISRN
FOI-R--1703--SE

Klassificering
Teknisk rapport

Forskningsområde
5. Bekämpning och skydd

Månad, år
Augusti 2005

Projektnummer
E2036

Delområde
51 VVS med styrda vapen

Delområde 2

Författare/redaktör
Lars Olovsson
Tommie Sundel
Anders Tjernberg
Bo Johansson

Projektledare
Bo Johansson

Godkänd av

Uppdragsgivare/kundbeteckning
Försvarsmakten

Tekniskt och/eller vetenskapligt ansvarig

Rapportens titel
Finita elementsimuleringar av tryckverkan från minor - en konvergensstudie med GRALE2D

Sammanfattning

Detta arbete är en konvergensstudie med syftet att arbeta fram riktlinjer för axisymmetriska finita elementberäkningar med GRALE2D av effekten från detonerande minor. Den, mot en plan stel yta på avståndet 50*cm*, reflekterade tryckpulsen har analyserats vid olika minstorlekar för såväl frilagda som nedgrävda laddningar. Modellens geometri och dimensioner valdes för att efterlikna en situation där ett fordon utsätts för en detonerande mina.

Resultaten indikerar vissa problem att nå konvergens för reflekterat tryck nära symmetriaxeln. Detta är extra tydligt i de fall minan täckts med ett lager sand. För globala resultat och impulsintensiteter uppvisar dock programmet generellt sett en god konvergens.

Rapporten avslutas med riktlinjer för val av elementstorlek vid olika laddningsstorlekar.

Nyckelord
GRALE2D, stötvåg, konvergensstudie

Övriga bibliografiska uppgifter

Språk Engelska

ISSN 1650-1942

Antal sidor: 36 s.

Distribution enligt missiv

Pris: Enligt prislista

Utökad sammanfattning

Numeriska simuleringar av fysikaliska förlopp är ofta kostnadseffektiva jämfört med att utföra verkliga prov (även om simuleringar måste kompletteras med verkliga prov). För att få tillförlitliga resultat från simuleringar är det viktigt att förstå hur programvaror för numeriska simuleringar fungerar. Hur fin måste modellen göras för att en tillförlitlig bedömning av verkan från en sprängladdning på ett fordon ska erhållas?

I inledande studier arbetar man med förenklade modeller för att sedan kunna gå vidare med ett komplett fordon eller delar av fordon när väl vetskap finns avseende erforderliga krav på de numeriska modellerna.

Detta arbete är en konvergensstudie med syftet att arbeta fram riktlinjer för axisymmetriska finita elementberäkningar med GRALE2D av effekten från detonerande minor. Den, mot en plan stel yta på avståndet $50cm$, reflekterade tryckpulsen har analyserats vid olika minstorlekar för såväl frilagda som nedgrävda laddningar. Modellens geometri och dimensioner valdes för att efterlikna en situation där ett fordon utsätts för en detonerande mina.

Resultaten indikerar vissa problem att nå konvergens för reflekterat tryck nära symmetriaxeln. Detta är extra tydligt i de fall minan täckts med ett lager sand. För globala resultat och impulsintensiteter uppvisar dock programmet generellt sett en god konvergens.

Rapporten avslutas med riktlinjer för val av elementstorlek vid olika laddningsstorlekar.

Contents

1 Introduction

Setting up a numerical model for the simulation of any physical process requires careful considerations. Firstly, assumed governing equations and boundary conditions must capture the essentials of the process that is to be analysed. Secondly, the numerical solution to the posed equations must be accurate enough to meet established requirements.

The physical process considered in this work is a detonating mine, the generated shock wave and its interaction with a rigid flat surface. It is important to note that geometries and dimensions are chosen to resemble the situation of a vehicle exposed to a mine blast. Results and conclusions are to be utilized in future simulations of mine blasts and their interaction with real structures.

For the specific case of this study, with todays simulation tools at hand, the dominating challenges are to be found on the numerical level. Extreme pressure gradients at the shock front are not trivially treated with a finite element modelling technique. Unwanted numerical effects tend to continuously smear out the pressure front in a non-physical manner and the effect of a given mine is generally underestimated. Improved numerical schemes and refined spatial discretizations are ways to deal with this problem. To avoid time consuming convergence studies for each new case, user guidelines for spatial discretization and for parameters controlling the numerical solution procedures are of utmost importance. Such guidelines naturally become software dependent and this work focuses on the FOI in-house finite element software GRALE2D.

The report is essentially a convergence study of the reflected pressure pulse against a rigid flat surface, for a specific stand-off distance but for different charge sizes. Both surface laid and buried mines have been considered. Chapter 2 presents the different test cases and the simulation models. The results are presented in Chapter 3. Based on the results, some conclusions and user guidelines are given in Chapter 4.

2 Test cases and numerical models

Both surface laid and buried mines are realistic cases for future mine blast analyses. For that reason, two different test cases have been defined with the objective to analyse the accuracy and convergence properties of GRALE2D. From a numerical modelling point of view, at small stand-off distances, buried and surface laid mines are fundamentally different. In the case of a surface laid mine the impulse is transmitted to the structure, via the air, as a shock wave. Resolving the shock front and keeping the numerical dissipation errors on an acceptable level requires a relatively dense finite element grid. Once the mine is covered by a layer of soil, the air plays a less central role in the impulse transmission. Instead, it is the soil ejecta impacting the structure that needs to be accurately described.

2.1 Test cases

The first test case was a surface laid mine, where the generated shock wave interacted with a plane rigid surface $50cm$ above ground. The ground was assumed rigid. The second case was geometrically equivalent to the first one,

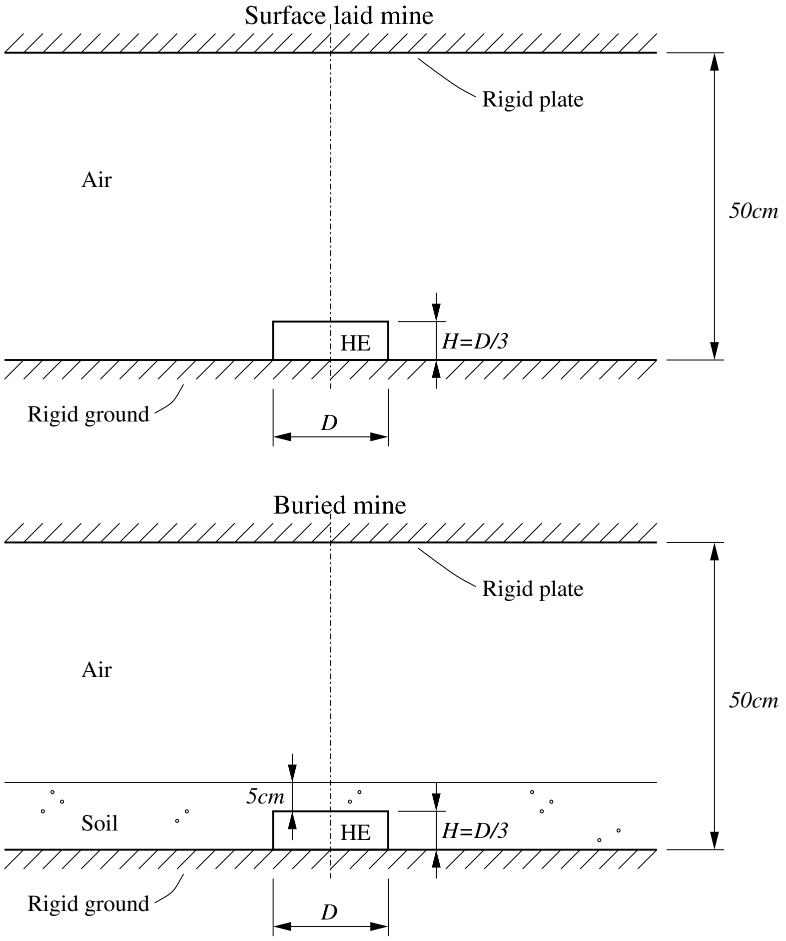


Figure 1: Test cases for the simulation of surface laid and buried mines.

except that the mine was covered by a layer of soil. Both cases are depicted in Figure 1. The high explosive charge size was set to 2, 4 and $8kg$. The diameter-height ratio of the charge was defined as $D/H = 3$.

2.2 Material models

2.2.1 High explosive

The high explosive material (generic plastic explosive) was modelled using the JWL equation of state (programmed burn), c.f. Lee et al. [1].

$$p = A(1 - \frac{\omega}{R_1 V})\mathrm{e}^{-R_1 V} + B(1 - \frac{\omega}{R_2 V})\mathrm{e}^{-R_2 V} + \omega e$$

where p is the pressure, $V = \rho_0/\rho$ is the ratio between initial and current densities and e is the specific internal energy per unit volume. A, B, R_1, R_2

and ω are material parameters. All parameters are given in Table 1, where D is the detonation velocity and p_{CJ} is the CJ-pressure.

ρ_0 $[g/cm^3]$	D $[cm/\mu s]$	A $[Mbar]$	B $[Mbar]$	R_1 $[-]$	R_2 $[-]$	ω $[-]$	e_0 $[Mbar\, cm^3/cm^3]$	p_{CJ} $[Mbar]$
1.630	0.693	3.712	0.03231	4.15	0.95	0.3	0.07	0.21

Table 1: Material properties of the high explosive.

2.2.2 Air

The air was treated as an ideal gas with constant heat capacities C_v and C_p and with the pressure defined as

$$p = \rho(C_p - C_v)T$$

where ρ is the density and T is the temperature of the air. All material constants are given in Table 2, where ρ_0 and T_0 are the ambient air density and temperature, respectively.

C_v $[Mbar\, cm^3/gK]$	C_p $[Mbar\, cm^3/gK]$	ρ_0 $[g/cm^3]$	T_0 $[K]$
$7.16 \cdot 10^{-6}$	$10.0 \cdot 10^{-6}$	$1.29 \cdot 10^{-3}$	300

Table 2: Material properties of the air.

2.2.3 Soil

For the soil, a simple tabulated pressure-compaction relationship was adopted and the deviatoric flow stress σ_y was assumed linearly proportional to the hydrostatic pressure with a cap according to

$$\sigma_y = \begin{cases} 0 & : p \leq 0 \\ a_1 p & : 0 < a_1 p \leq \sigma_{max} \\ \sigma_{max} & : a_1 p > \sigma_{max} \end{cases}$$

The compaction curve, representing soil samples from Sjöbo, was taken from Laine and Sandvik [2]. All material constants are given in Table 3 where K is the constant bulk modulus and ν is Poisson's ratio.

K $[Mbar]$	ν $[-]$	a_1 $[-]$	σ_{max} $[Mbar]$				
0.5	0	1.22	$2.26 \cdot 10^{-3}$				

ρ_0 $[g/cm^3]$	ρ_1 $[g/cm^3]$	ρ_2 $[g/cm^3]$	ρ_3 $[g/cm^3]$	ρ_4 $[g/cm^3]$	ρ_5 $[g/cm^3]$	ρ_6 $[g/cm^3]$	ρ_7 $[g/cm^3]$
1.6740	1.7390	1.8738	1.9970	2.1438	2.2500	2.4850	2.6713

p_1 $[MPa]$	p_1 $[MPa]$	p_2 $[MPa]$	p_3 $[MPa]$	p_4 $[MPa]$	p_5 $[MPa]$	p_6 $[MPa]$	p_7 $[MPa]$
0	4.58	15.0	29.2	59.2	98.1	289.4	650.7

Table 3: Material properties of the soil.

2.3 Discretization

In both cases a cylindrical region with radius $50cm$ was modelled from the ground to the target plate. That is, in an axi-symmetrical model, a $50 \times 50cm^2$ square was discretized with finite elements. Schematic pictures of the surface laid mine and buried mine models are given in figures 2 and 3, respectively.

Six different element sizes were tested, namely $h = 1, 1.5, 2.5, 5, 7.5$ and $10mm$. Table 4 shows the total number of elements N_{el} in the model for different element sizes.

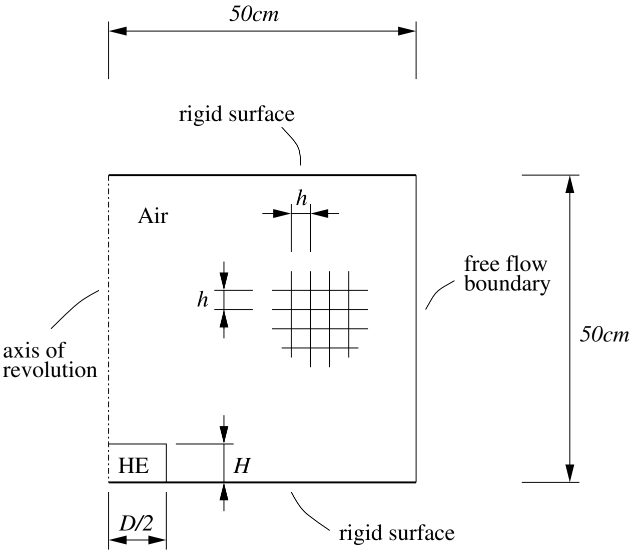


Figure 2: Discretized region for axi-symmetric surface laid mine simulations.

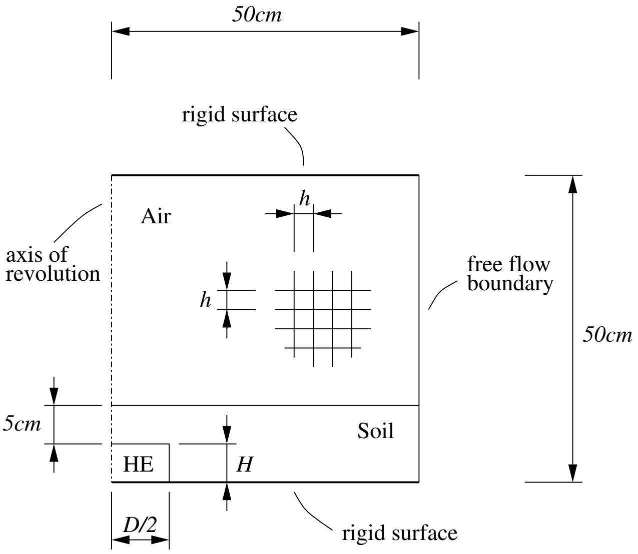


Figure 3: Discretized region for axi-symmetric buried mine simulations.

h $[mm]$	N_{el}
1.0	250,000
1.5	110,000
2.5	40,000
5.0	10,000
7.5	4,489
10.0	2,500

Table 4: Total number of elements for different element sizes.

2.4 Momentum transport scheme

GRALE2D possesses two different numerical schemes for the material flux related momentum transport between elements, c.f. Benson [3]. By default the program uses a spatially first order accurate scheme that is robust and computationally efficient. However, it is rather dissipative and poor at conserving kinetic energy in shock wave propagation applications. The second order scheme is less dissipative, but at the same time more dispersive. The dispersive effects may cause spatial oscillations in the velocity field.

In this study, both methods were tested for each combination of ground conditions, charge size and element grid discretization.

3 Results

Combining six different levels of finite element grid discretization, three HE charge sizes, two different ground conditions and two different momentum ad-

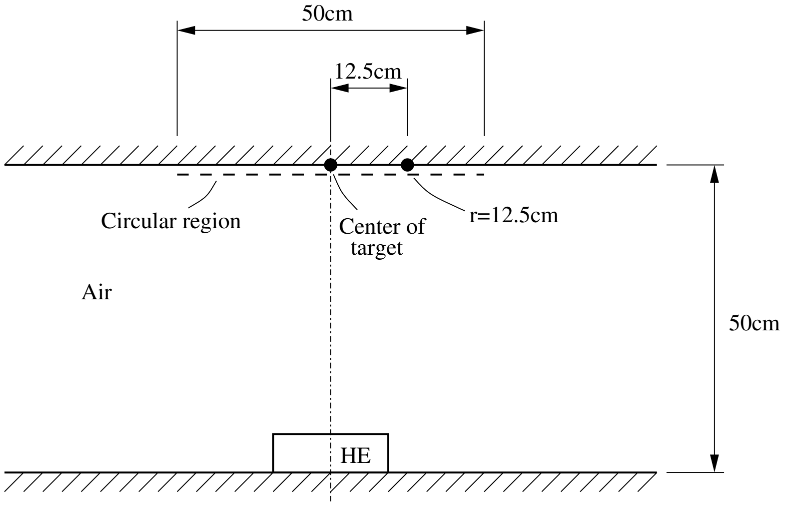


Figure 4: Pressure and impulse sampling points.

vection transport schemes rendered a total of 72 simulations. In addition, some comparing analyses ($2kg$ case) with the commercial finite element code AUTODYN have been carried out.

In order to keep the amount of processed and presented data on a reasonable level a few key quantities were chosen to represent the convergence properties of the code.

1. Peak pressure against the center of the target plate
2. Peak pressure at radial distance $r = 12.5cm$ from the center of the target plate
3. Peak average pressure against a circular region on the target plate with diameter $50cm$
4. Impulse intensity against the center of the target plate
5. Impulse intensity at radial distance $r = 12.5cm$ from the center of the target plate
6. Average impulse intensity against a circular region on the target plate with diameter $50cm$

The pressure and impulse sampling points are depicted in Figure 4. An evaluation of the obtained results shows that the most representative sampling point, in terms of performance and convergence properties, is at $r = 12.5cm$ (2nd order momentum advection). Hence, the results in this section are limited to this specific sampling point. For all extracted simulation results, including those obtained with AUTODYN, the reader is referred to the Appendix (the content of each specific diagram follows from the caption text).

3.1 Surface laid mines

Figure 5 shows the monitored pressure and impulse data at $r = 12.5cm$, using 2nd order momentum advection, for different element sizes and HE charge sizes. The CPU-time required to complete $1ms$ of physical time ranged between roughly 50 seconds for $h = 10mm$ to 15 hours for $h = 1mm$. The computer used for the simulations was a standard Linux desktop computer (Intel P4, 3.2GHz). All simulations were carried out in double precision.

3.2 Buried mines

Figure 6 shows the monitored pressure and impulse data at $r = 12.5cm$,using 2nd order momentum advection, for different element sizes and HE charge sizes. The CPU-time required to complete $2ms$ of physical time ranged between roughly 4 minutes for $h = 10mm$ to 45 hours for $h = 1mm$.

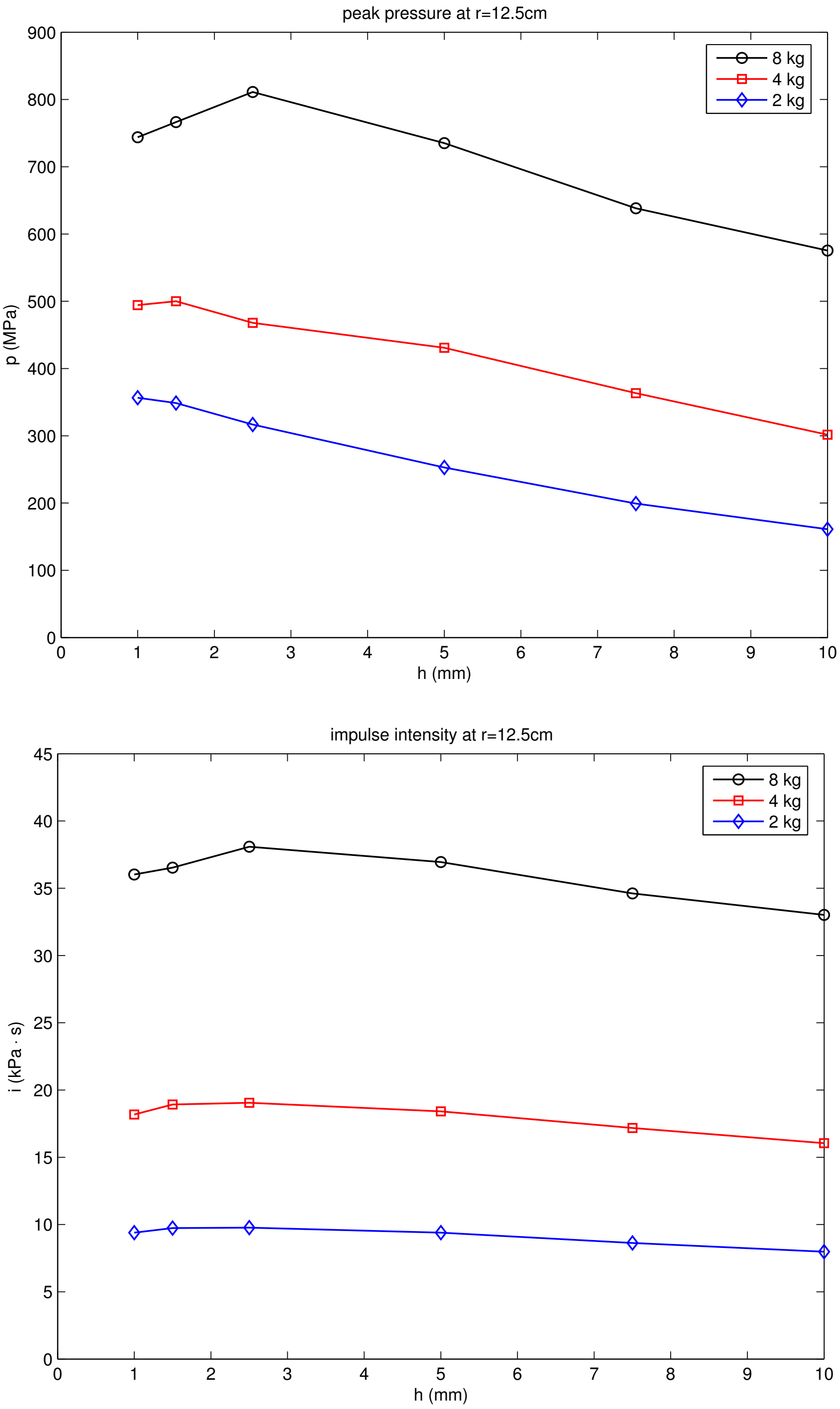


Figure 5: Peak pressure and impulse intensity at $r = 12.5cm$ for surface laid mines using 2nd order momentum advection.

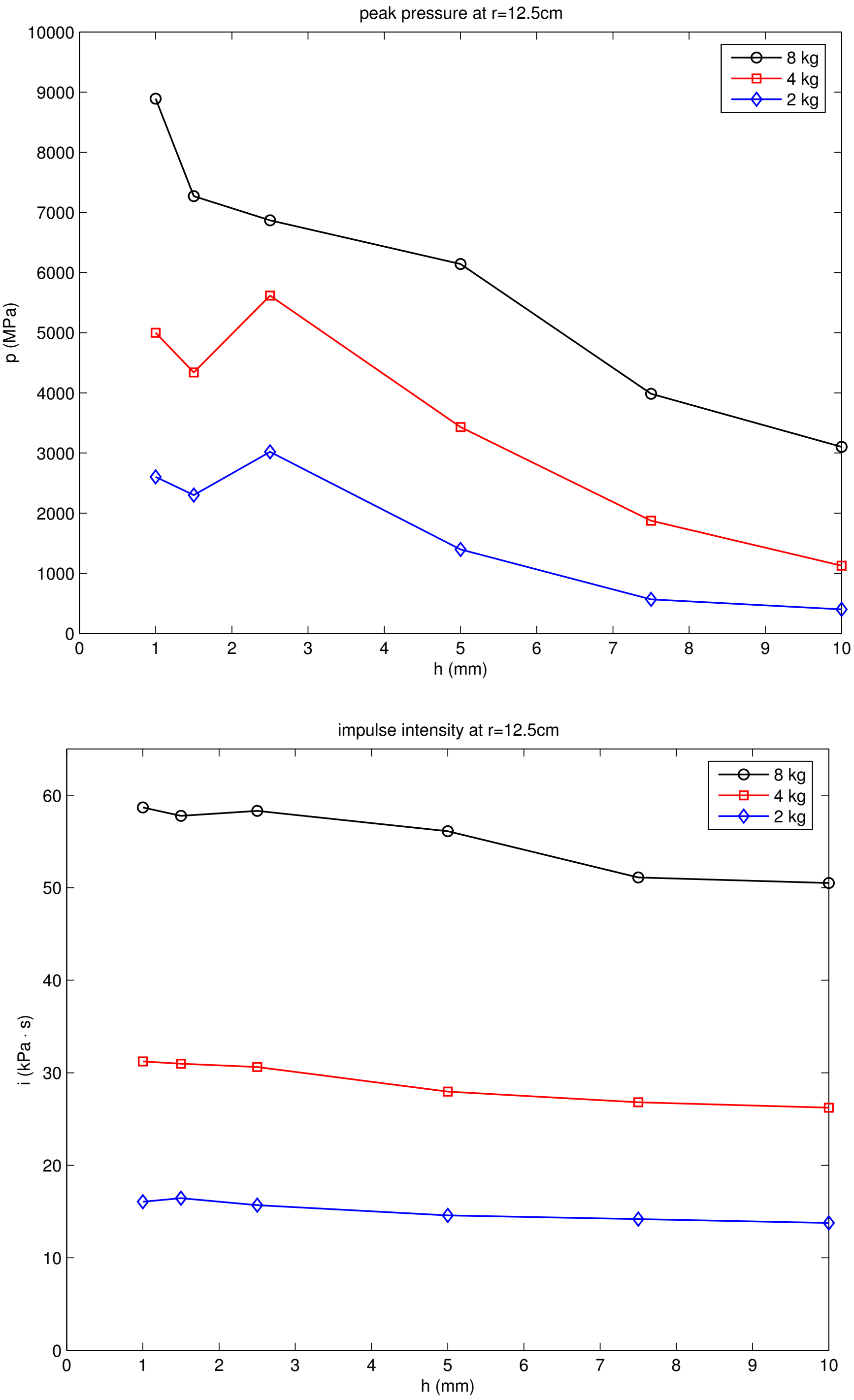


Figure 6: Peak pressure and impulse intensity at $r = 12.5cm$ for buried mines using 2nd order momentum advection.

4 Discussion and conclusions

Depending on what quantities one tries to capture with the numerical simulations, the obtained results in this study indicate bad as well as reasonably good convergence properties of the code:

- There is a generally bad convergence of local peak pressure levels. The obtained levels are not always reliable even for the smallest tested element size $h = 1mm$. This is the case for surface laid as well as for buried mines.

- Impulse intensities converge within the span of tested element sizes, except near the axis of revolution. It is interesting to note that AUTODYN suffers from similar convergence problems as GRALE2D near the axis of revolution.

- In all investigated cases, buried mines produce larger impulses than surface laid ones.

- The 2nd order momentum transport scheme is always to be recommended. The 2nd order scheme greatly improves the convergence of impulse intensities at a negligible additional computational cost. It can be noted that, as of today, a 2nd order momentum transport scheme is not implemented in AUTODYN (version 5).

- The results converge faster for large than for small charge sizes.

- Reliable results on average pressures and impulses require considerably less fine element grids than local quantities (in space as well as time). Hence, based on the obtained results it is not possible to give general element size recommendations. It all depends on what one tries to capture with the numerical simulations and on specific accuracy requirements. It is left to the reader to interpret and utilize the results for his or her specific needs.

- Most explicit finite element codes are similar in terms of performance and numerical methods used for the solution procedure (in both two- and three-dimensional contexts). Hence, even though the results presented here are specific for GRALE2D, it is believed that they can be used as a guidance when setting up element grids in future projects using different codes such as e.g. AUTODYN and LS-DYNA. However, a few preparing simulations will be necessary in order to verify the similarity between the codes.

References

[1] E.L. Lee, H.C. Homig, J.W. Kury, *Adiabatic expansion of high explosive detonation products*, LLNL Technical Report, UCRL-50411, 1968.

[2] L. Laine and A. Sandvik, *Derivation of mechanical properties for sand*, 4th SILOS, CI-Premier Ltd., p361-367, 2001.

[3] D.J. Benson, *Computational methods in Lagrangian and Eulerian hydrocodes*, Computer Methods in Applied Mechanics and Engineering. **99** (2-3), p235-394, 1992.

Appendix

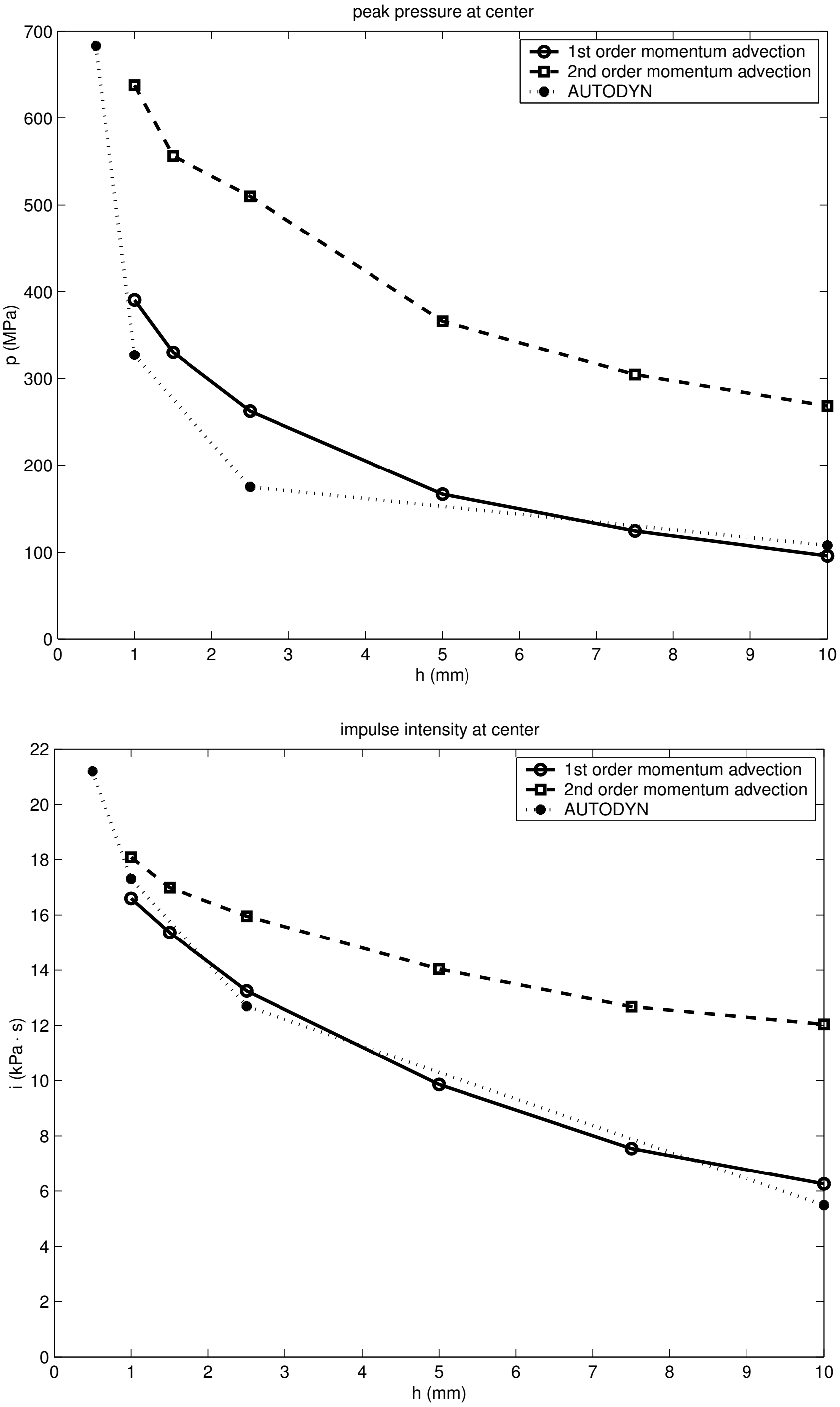


Figure 7: Peak pressure and impulse intensity at the target plate center for $2kg$ surface laid mines.

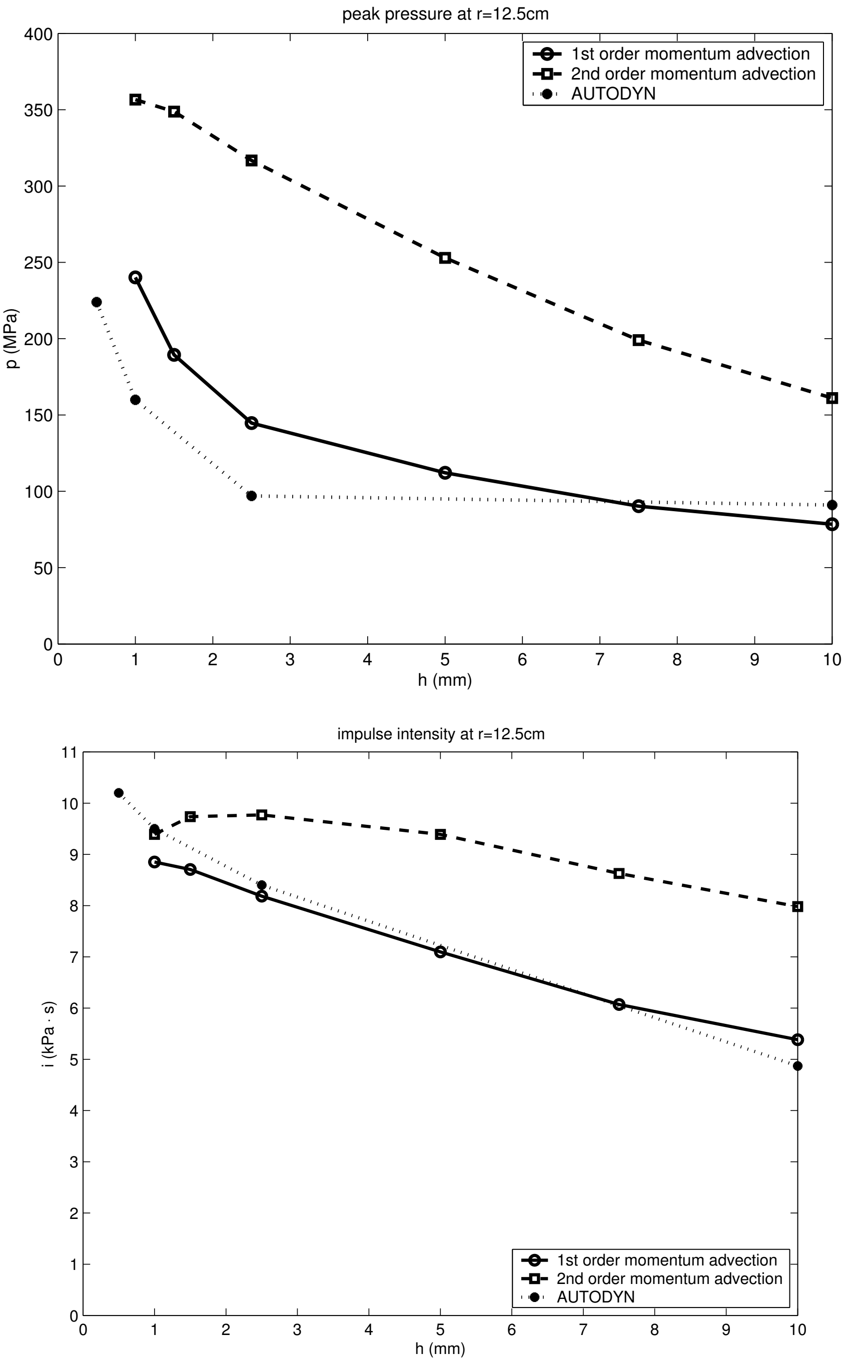


Figure 8: Peak pressure and impulse intensity at $r = 12.5cm$ for $2kg$ surface laid mines.

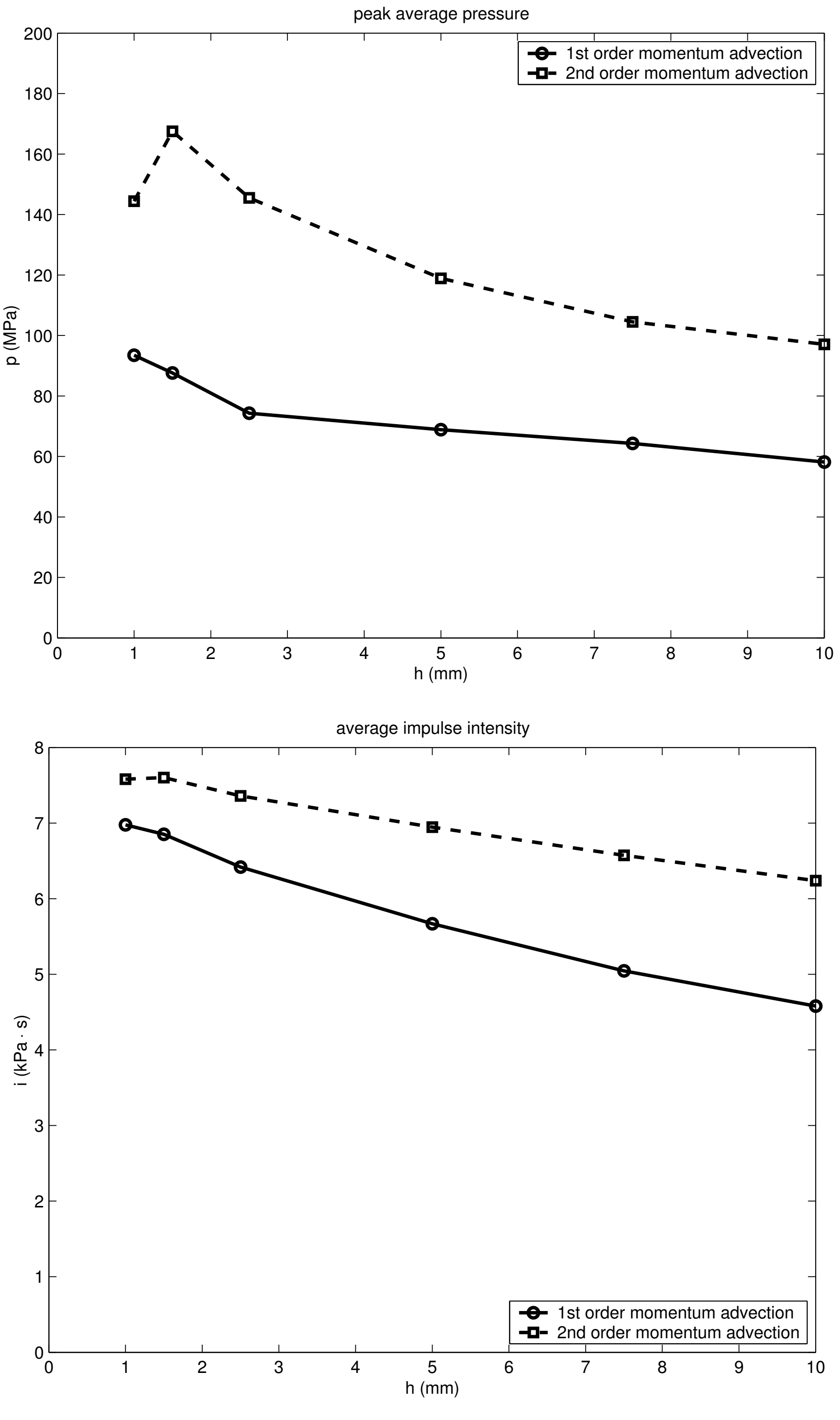
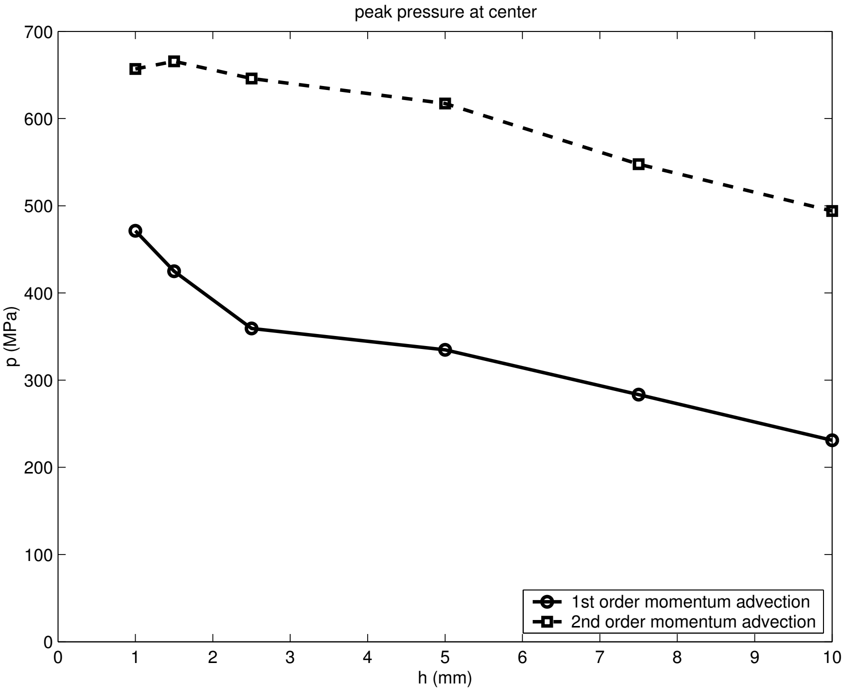


Figure 9: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $2kg$ surface laid mines.



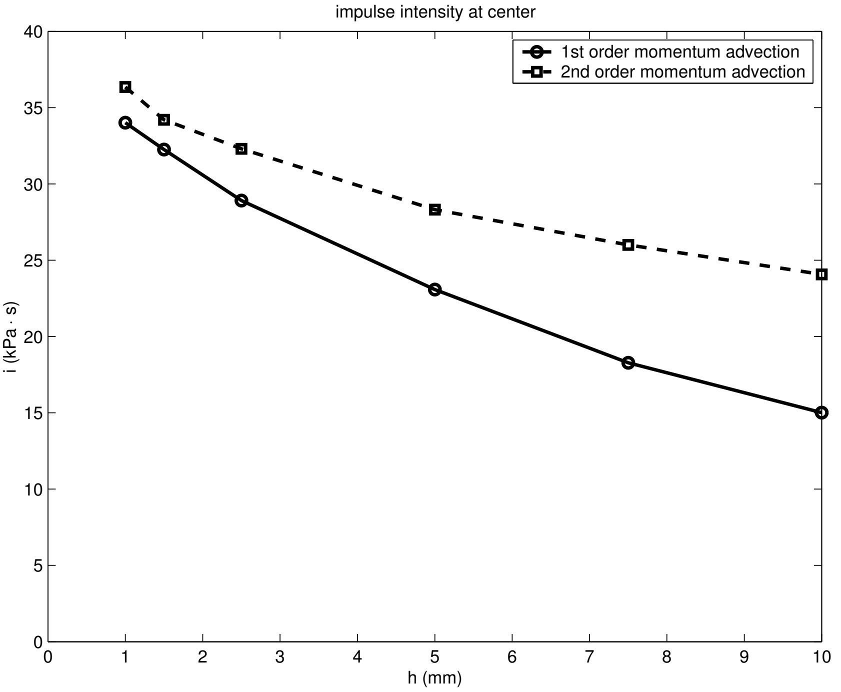


Figure 10: Peak pressure and impulse intensity at the target plate center for $4kg$ surface laid mines.

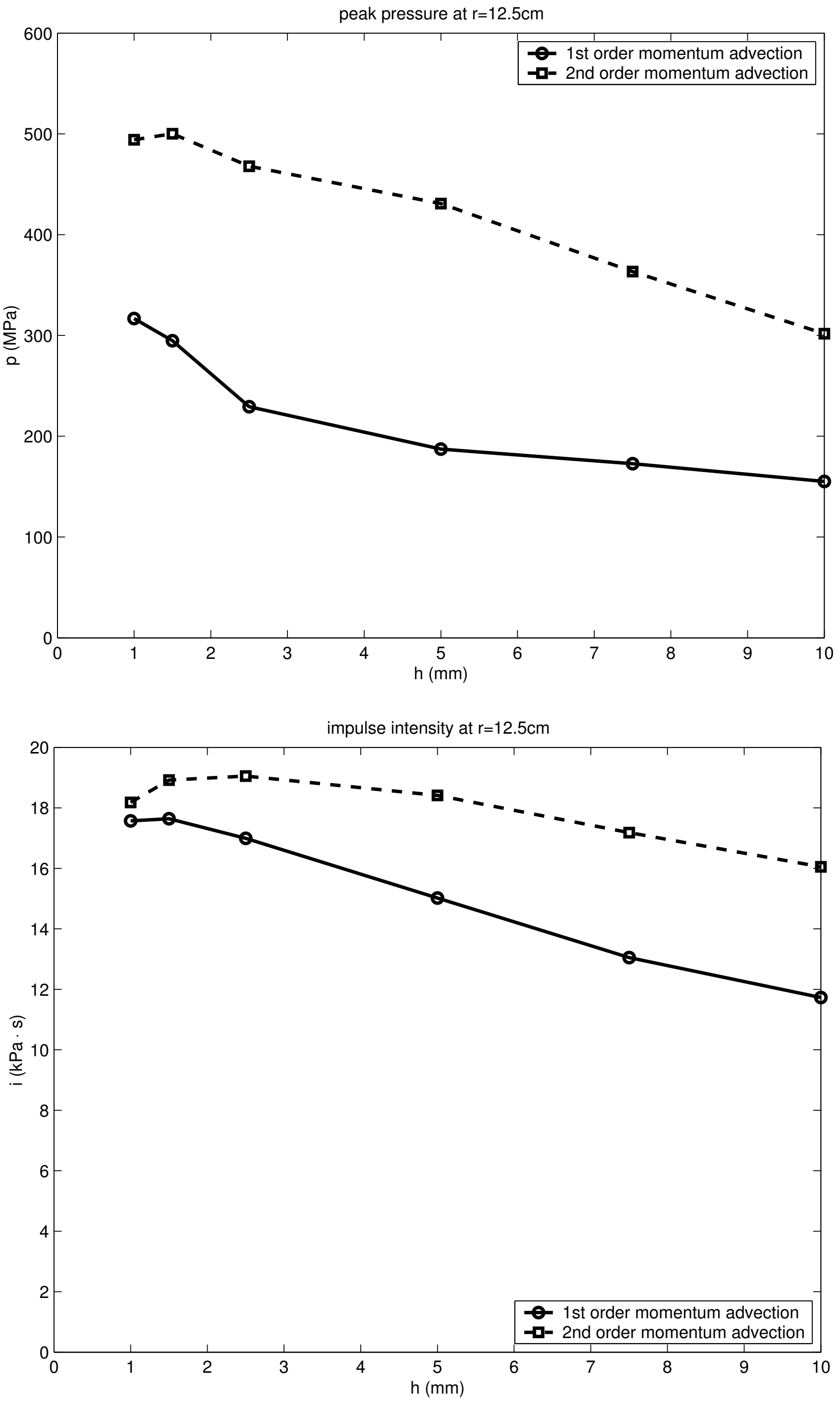


Figure 11: Peak pressure and impulse intensity at $r = 12.5cm$ for $4kg$ surface laid mines.

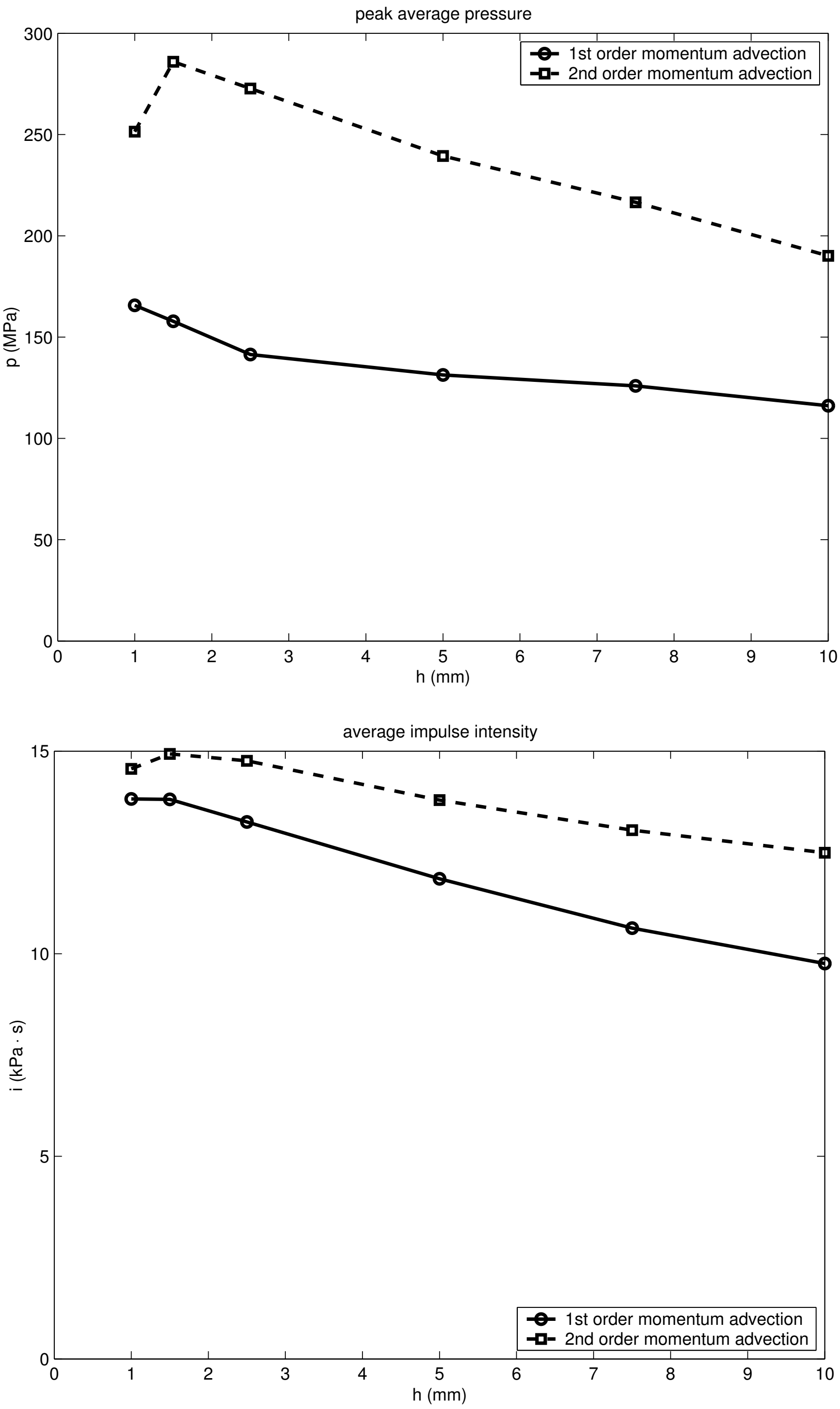


Figure 12: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $4kg$ surface laid mines.

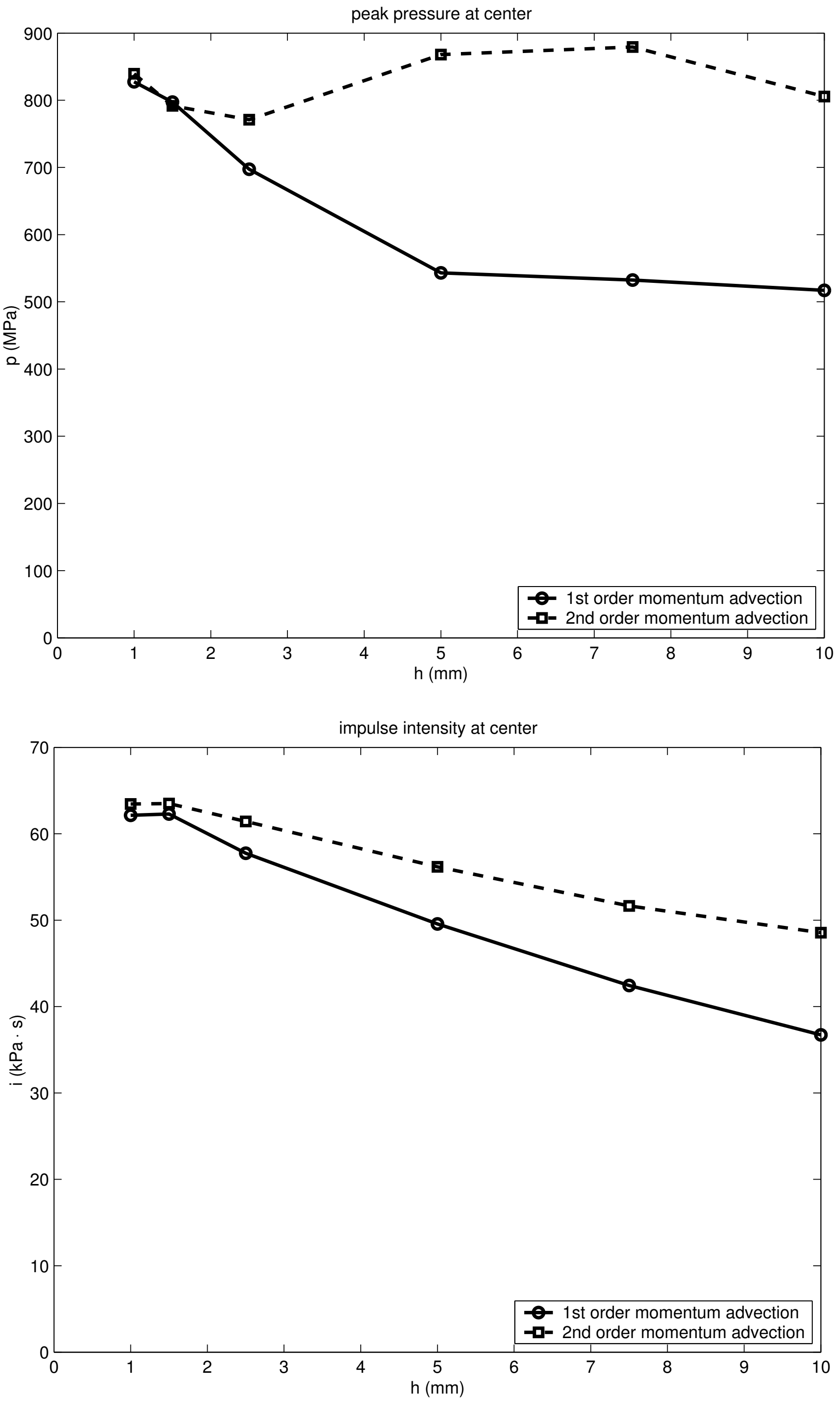


Figure 13: Peak pressure and impulse intensity at the target plate center for $8kg$ surface laid mines.

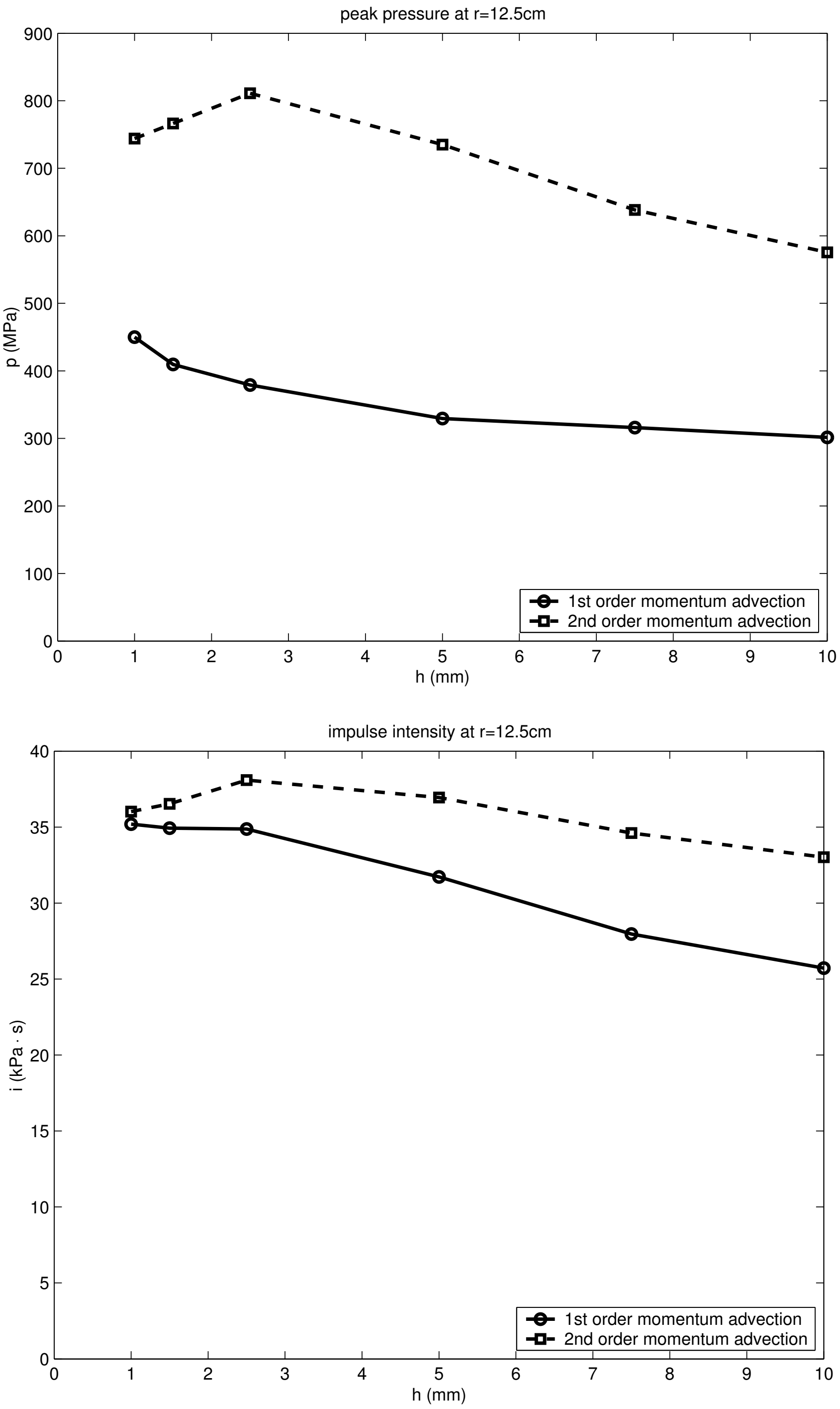


Figure 14: Peak pressure and impulse intensity at $r = 12.5cm$ for $8kg$ surface laid mines.

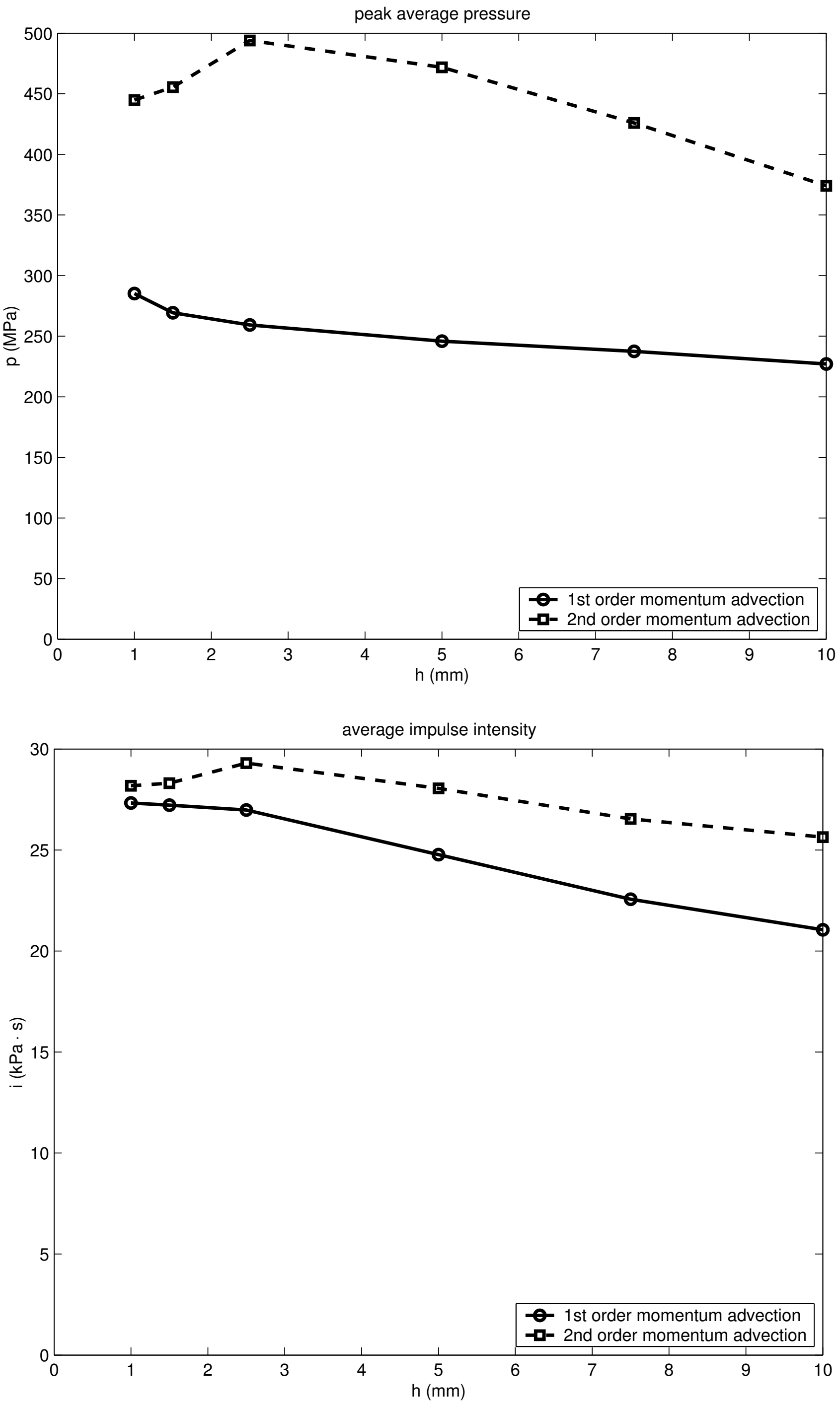


Figure 15: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $8kg$ surface laid mines.

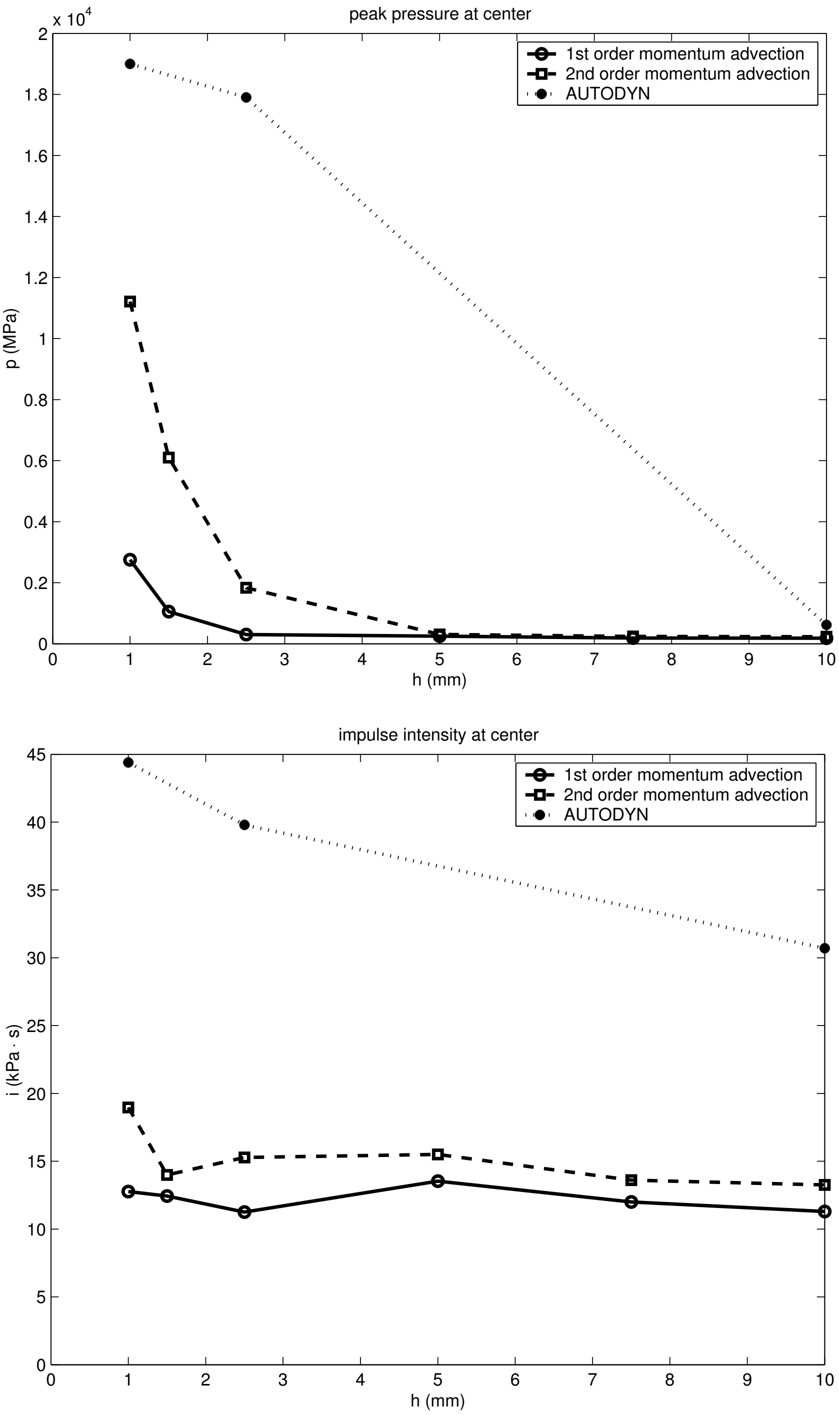


Figure 16: Peak pressure and impulse intensity at the target plate center for $2kg$ buried mines.

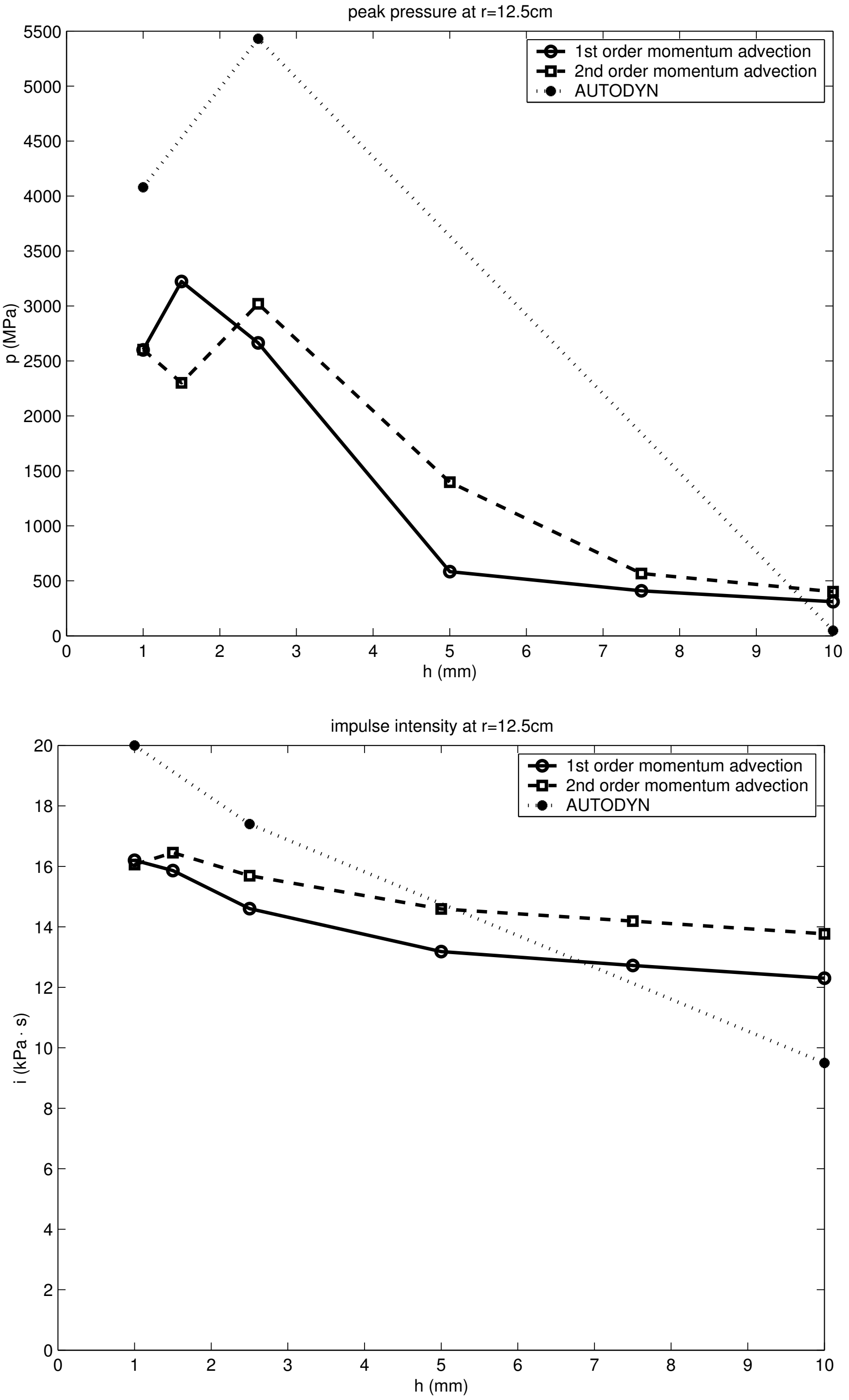


Figure 17: Peak pressure and impulse intensity at $r = 12.5cm$ for $2kg$ buried mines.

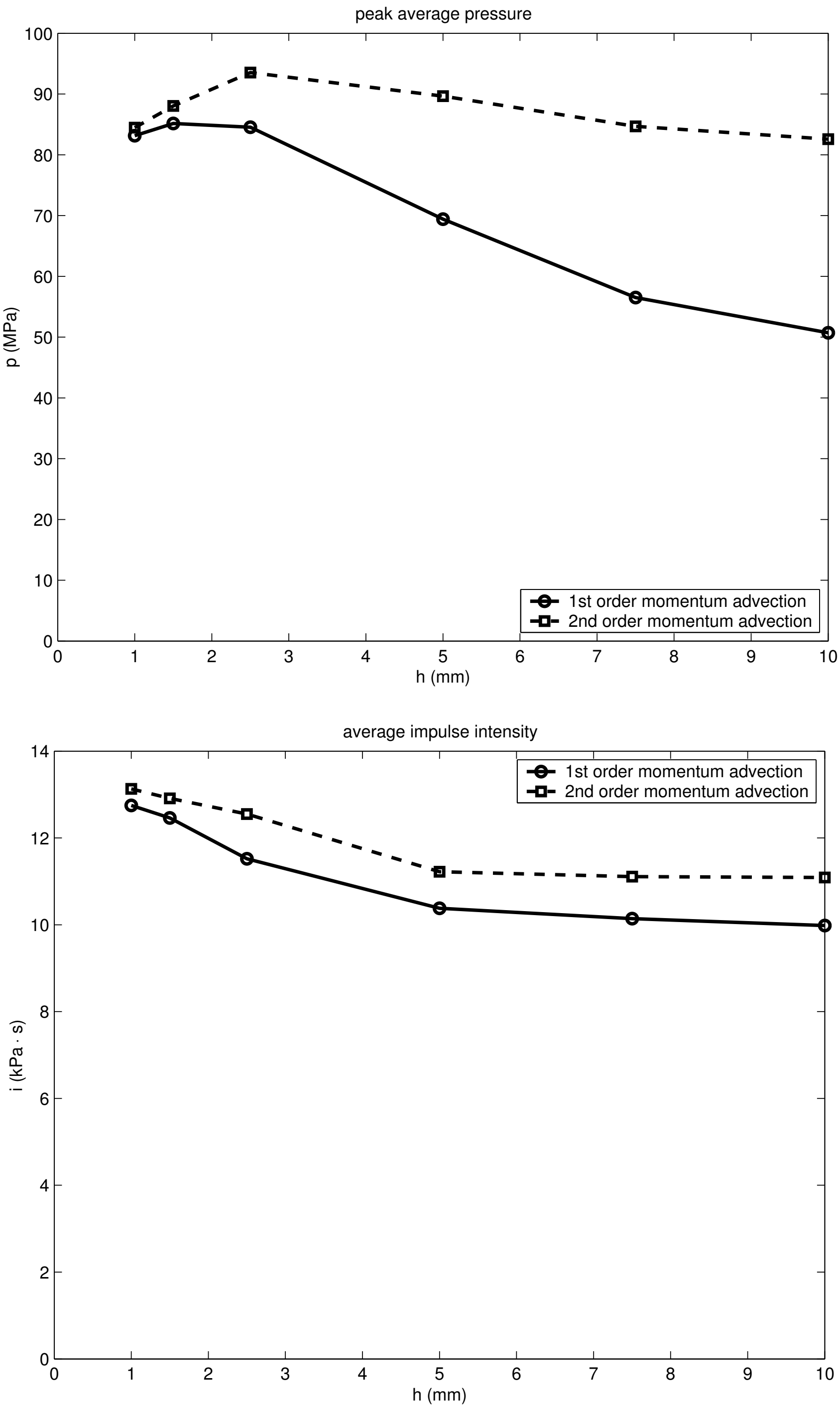


Figure 18: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $2kg$ buried mines.

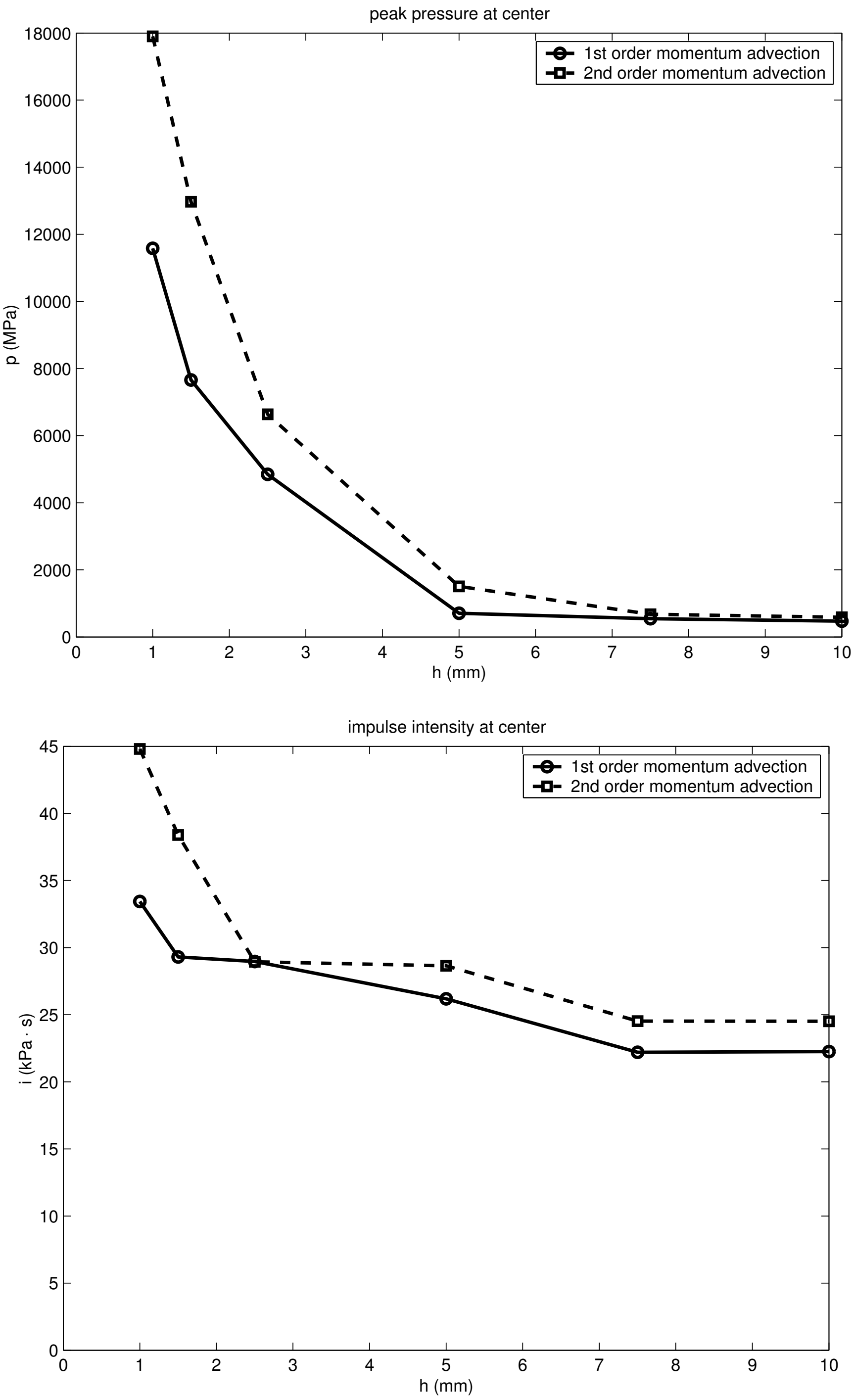


Figure 19: Peak pressure and impulse intensity at the target plate center for $4kg$ buried mines.

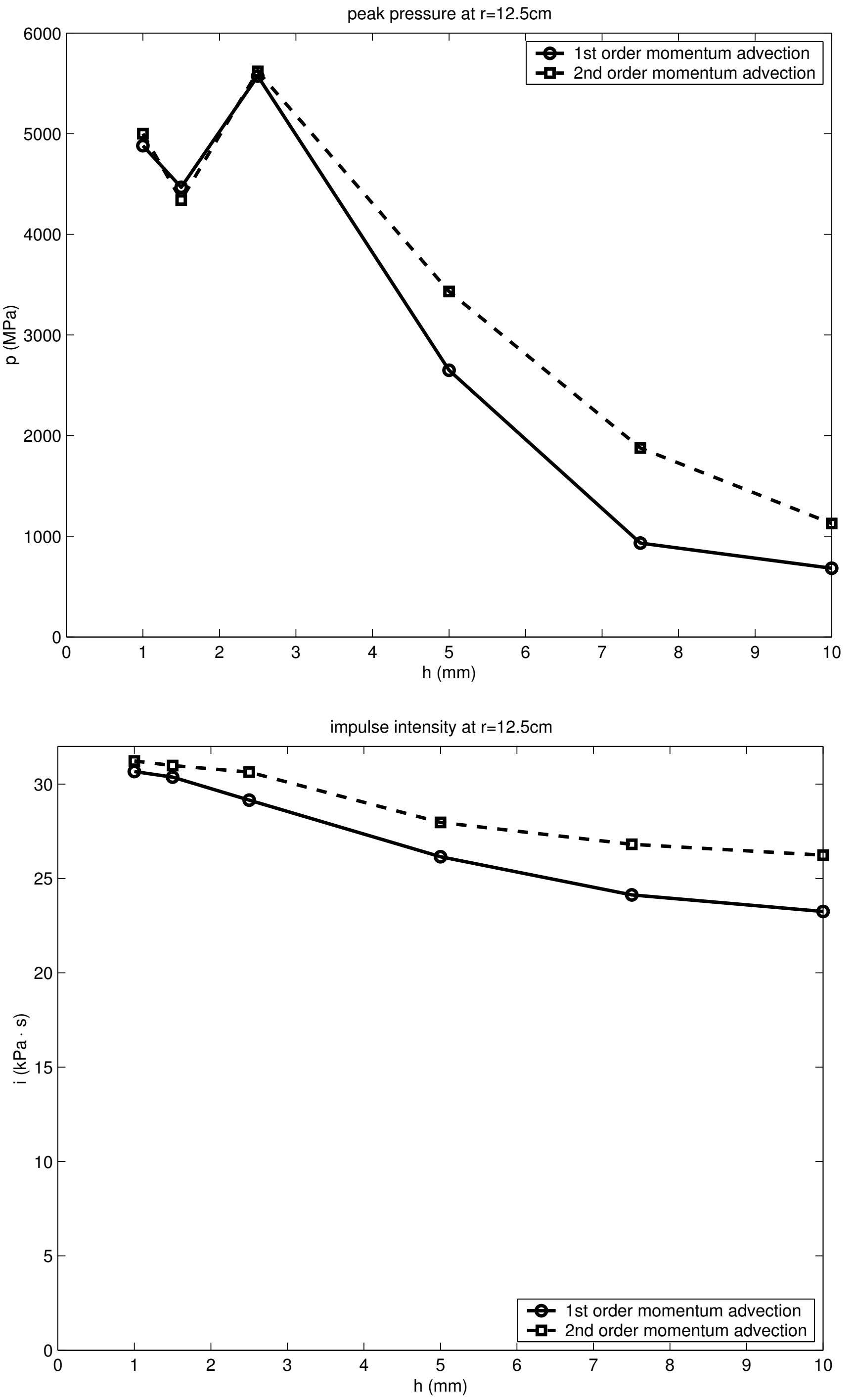


Figure 20: Peak pressure and impulse intensity at $r = 12.5cm$ for $4kg$ buried mines.

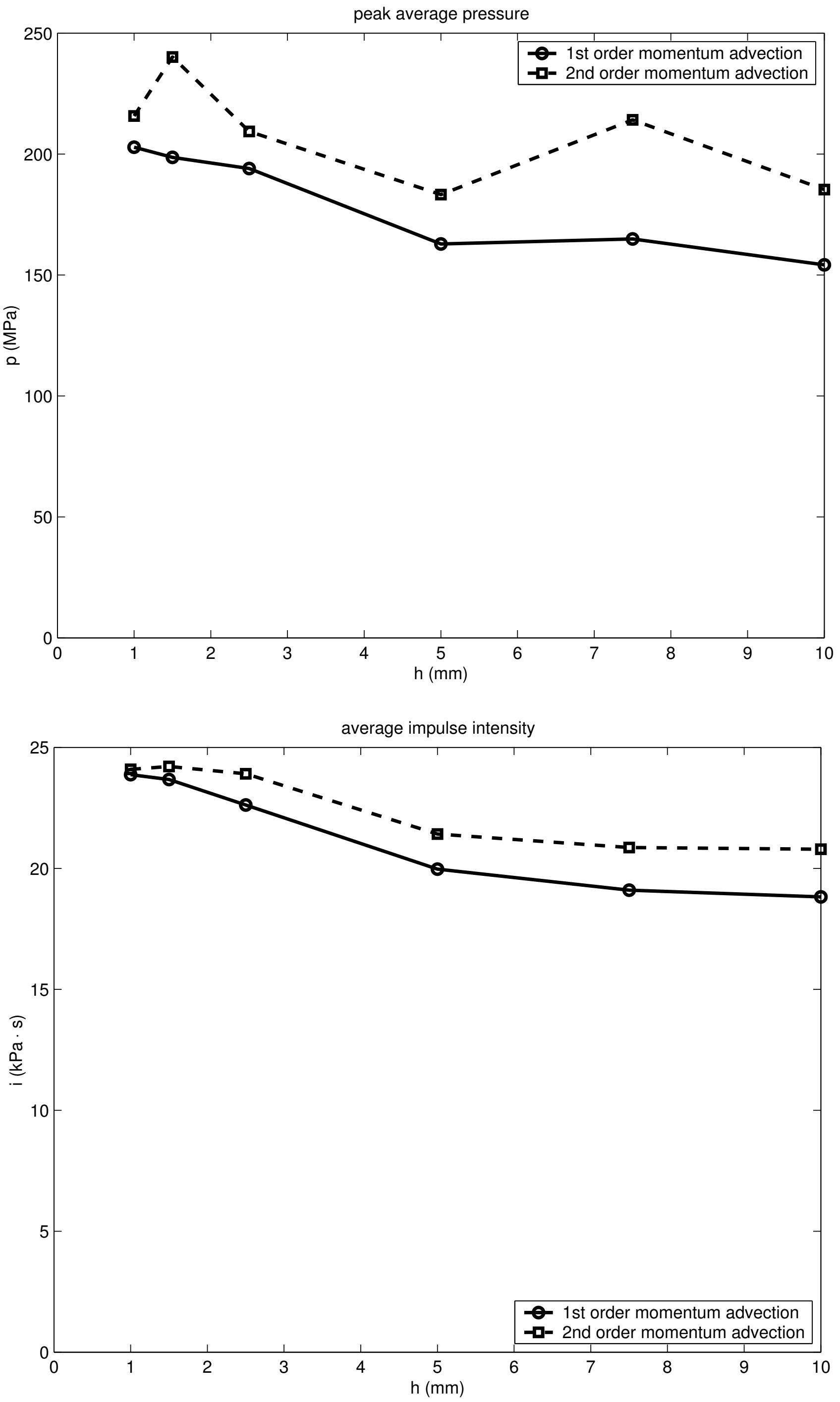


Figure 21: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $4kg$ buried mines.

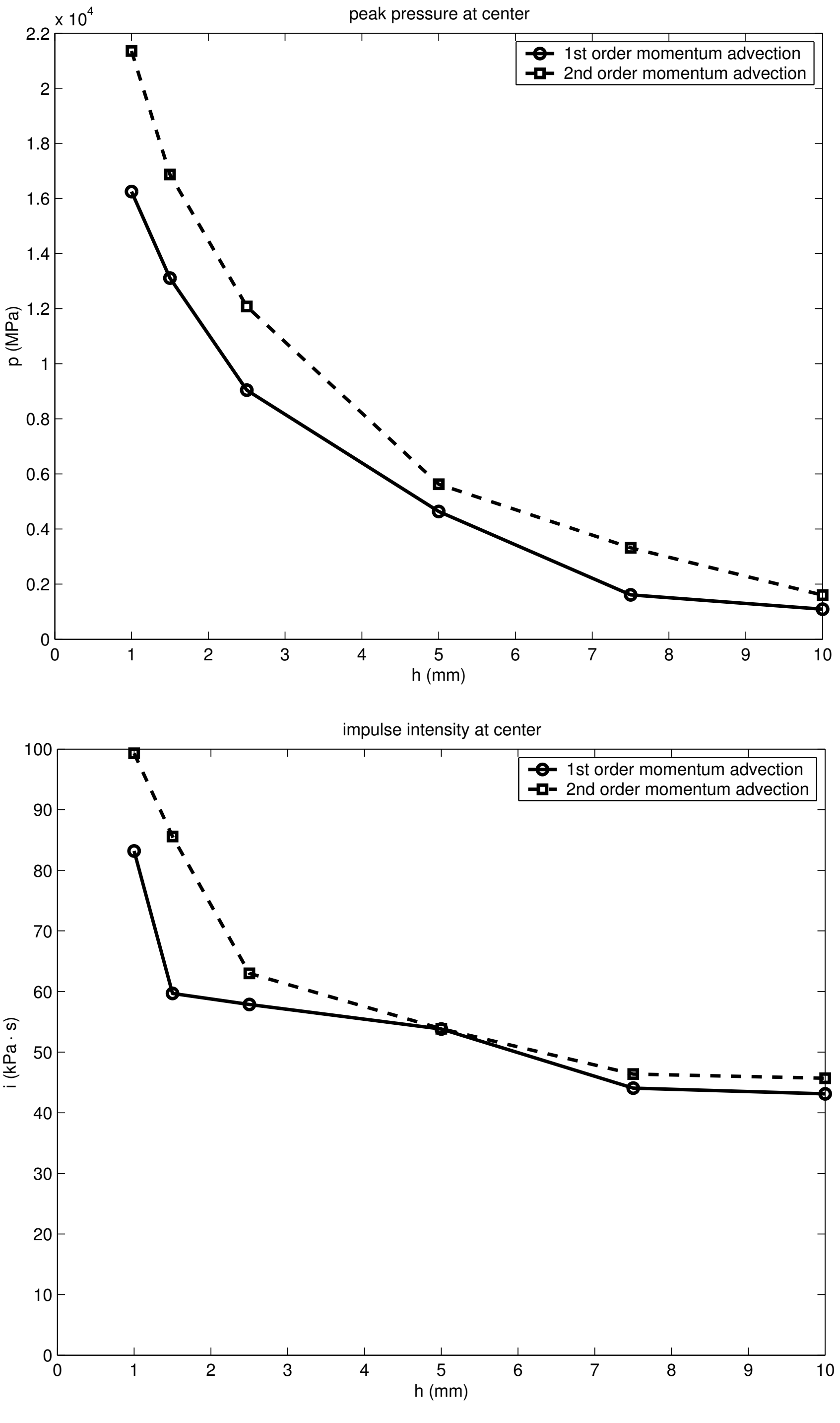


Figure 22: Peak pressure and impulse intensity at the target plate center for $8kg$ buried mines.

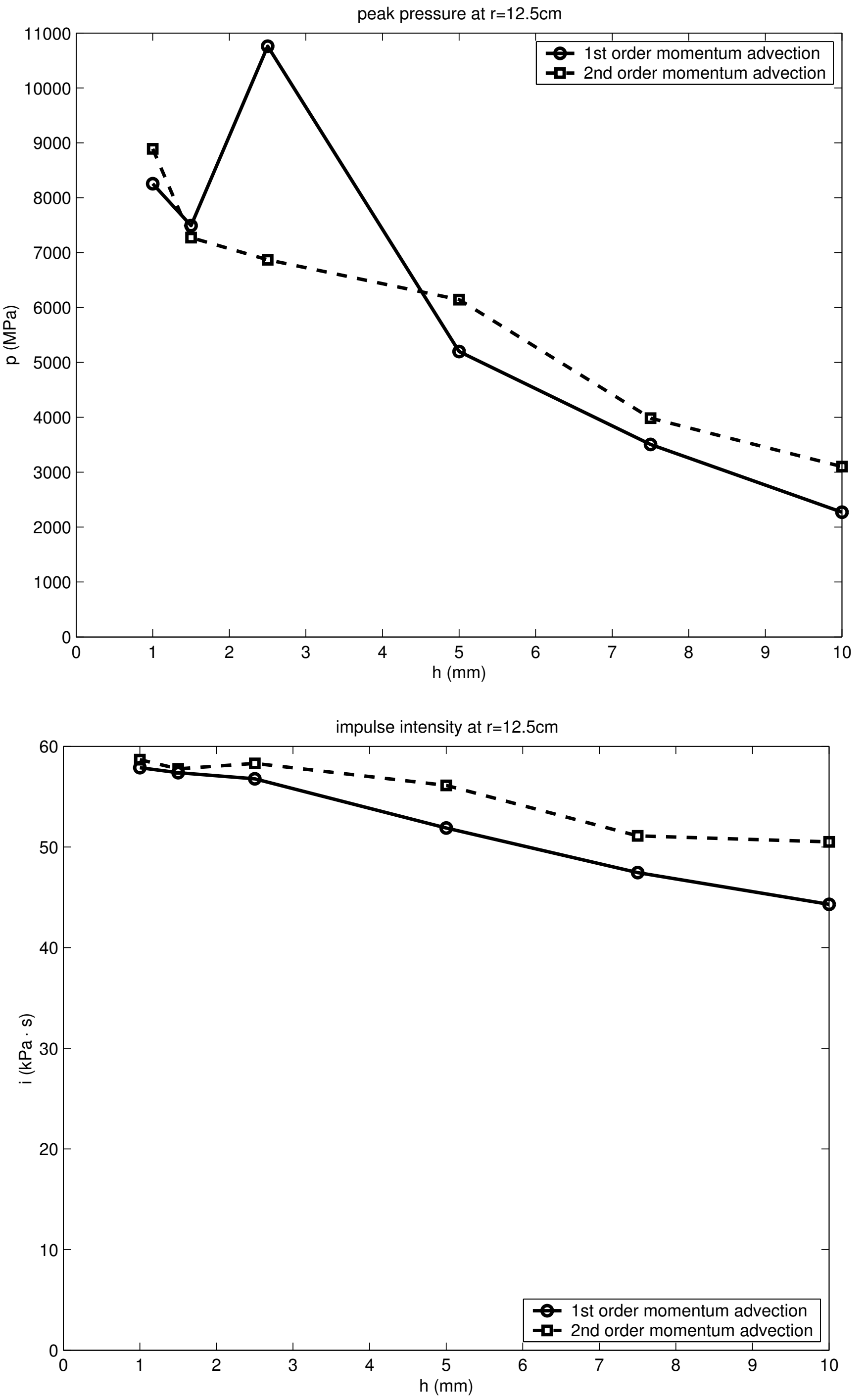


Figure 23: Peak pressure and impulse intensity at $r = 12.5cm$ for $8kg$ buried mines.

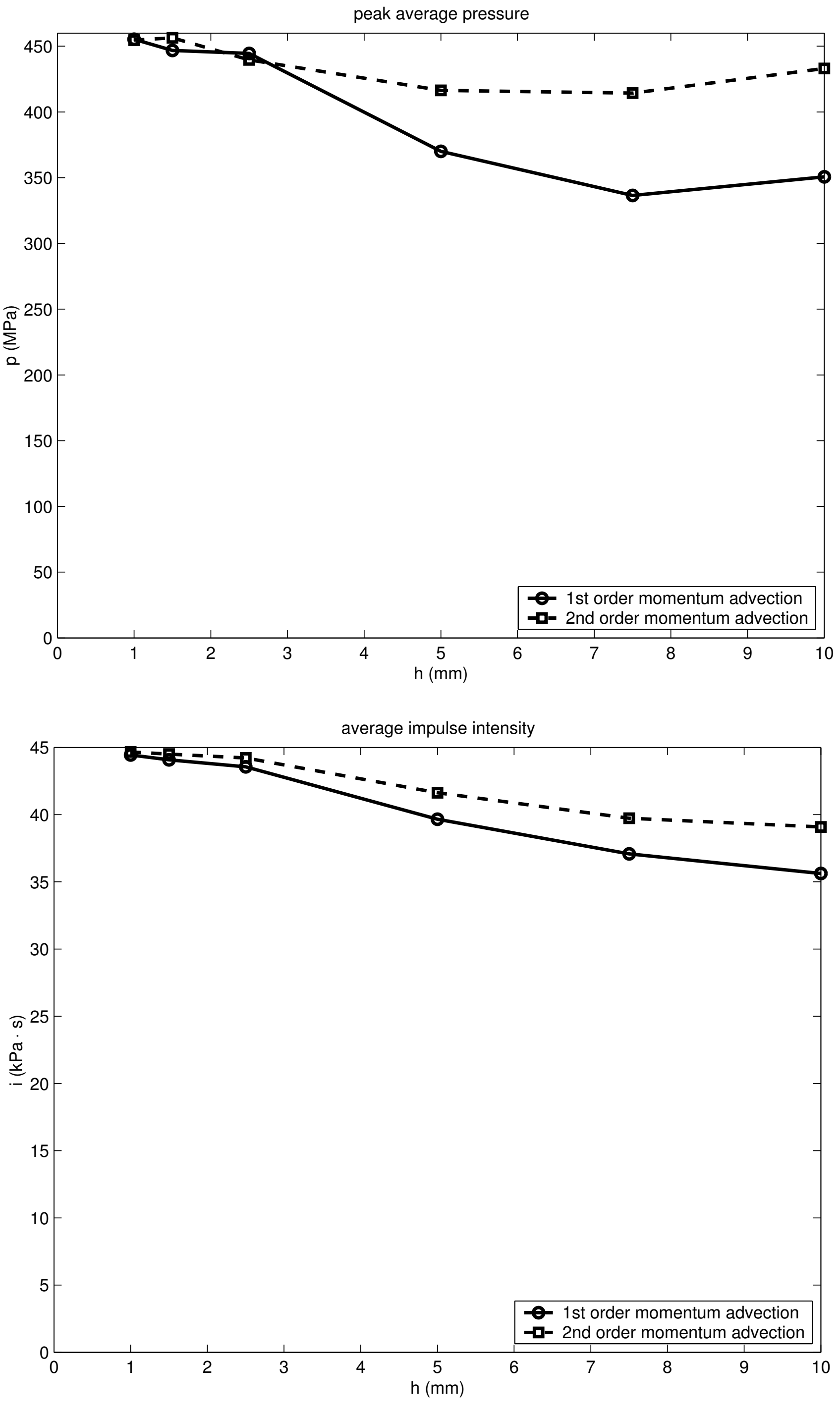


Figure 24: Maximum average pressure and impulse intensity against circular region with diameter $50cm$ for $8kg$ buried mines.