SURFACE BLAST MODELING USING AIR3D

1.1 Introduction

The blast analyses of structures using commercial finite element software programs, like LS-Dyna, model the blast loading as time-dependent point or distributed loads applied directly to the structure. These time-dependent loads can be determined using two methods: 1) Through the charts developed by Biggs (1964), DoD (2008) and PDC-TR-06-01 (2008), and 2) Through the computational fluid dynamics analysis. The first method was discussed in the previous assignment.

Surface blast loading on the column is obtained here using the software program Air3D, which uses computational fluid dynamics (CFD) approach. The time and space discretization used in Air3D provides a more realistic approach to simulate blast loading on structures. A three-dimensional analysis was performed here to generate the pressure histories and other blast loading parameters at monitoring points defined in the problem. The analysis results are verified against those reported in homework assignment 4. Analyses were performed using four different mesh sizes to check the sensitivity of response quantities to varying mesh sizes.

Theory discussed in this report is based on the material presented in user's manual of Air3D (Rose, 2006). The Air3D input file used here for the three-dimensional analysis was built on the example 3 in the user's manual.

1.2 Model Development

1.2.1 Column section

A W14×257 steel column section was used for the analysis. Additional properties of the column are presented in Table 1.

Table 1: Properties of used for analysis

Property	Notation	Value
Cross-sectional area	A	0.04855 m^2
Moment of inertia about strong axis	I	1.415×10^{-3} m^4
Mass per unit length	m	382.48 Kg/m
Modulus of elasticity	E	2.07×10^{11} N/m^2
Length	L	5 m
Mass density	ρ	7830 Kg/m^3

Response of column is monitored at five height locations, with two monitoring points at each height. The two monitoring points at each height is located at the center of the meshes at the middle and end of the flange, respectively, as shown in Figure 1.

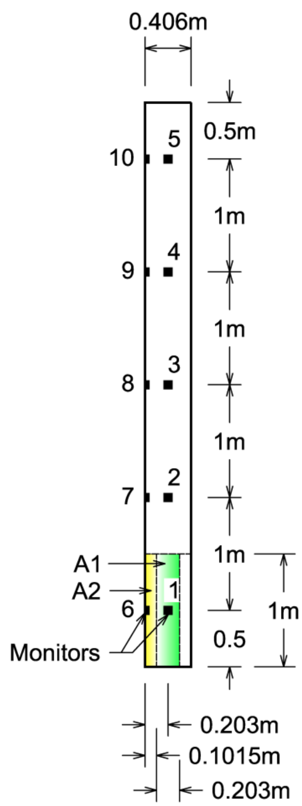

Figure 1: Location of the monitoring points

It should be noted while assigning location of monitoring points in the modal that if monitoring points are located just above the surface of column, they record incident overpressure history, and if they are on the surface of the column, reflected overpressure history is recorded. For the analyses considered here, reflected overpressure histories are measured.

1.2.2 Explosive properties

The explosive (charge) is assumed to be of spherical shape here. The properties of the charge are presented in Table 2.

Table 2: Properties of the charge

Parameter	Value				
Locations	1	2	3	4	5
Mass of the charge (kg)	500	500	500	500	500
Standoff distance (m)	3	3.25	3.91	4.80	5.83
Scaled distance $(m/kg^{0.333})$	0.38	0.41	0.49	0.60	0.73

The radius of the charge is calculated from the specified charge mass $W\,(500\,kg)$ and the density of the condensed explosive $\rho_{TNT}\,(1.6\times10^3\,kg/m^3)$ as:

$$r_{TNT} = \left(\frac{3}{4\pi}\frac{W}{\rho_{TNT}}\right)^{\frac{1}{3}} = 0.42\,m$$

1.2.3 Numerical model in Air3D

A three-dimensional model of the blast of loading of column was developed in Air3D. The geometric modeling capability of Air3D is limited to rectangular objects and it cannot consider buildings/objects aligned obliquely to Cartesian grid. Although, W shaped beam can be modeled, for blast loading calculations, only the area of the face of flange (facing the detonation) and overall dimensions of the are important. Hence the column was modeled as a rectangular shaped block without any significant loss of accuracy. The explosive (or charge) is placed at the origin of the three-dimensional model. Only half of the column is modeled to take advantage of the symmetry of the problem. A screen-capture of the model used in Air3D is shown in Figure 2.

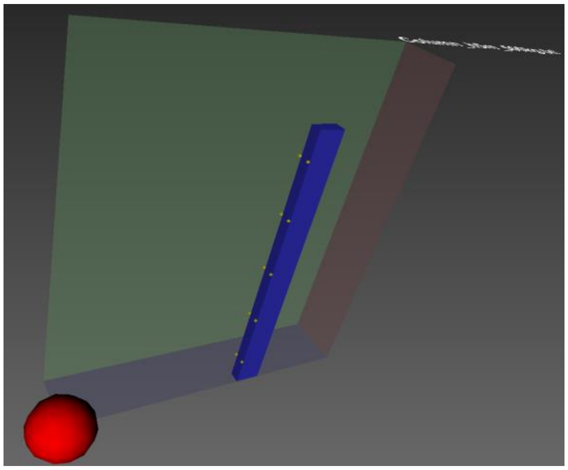

Figure 2: Three-dimensional model in Air3D

The yellow dots shown in the figure are the monitoring points defined in the model. In three-dimensional analysis, charge can be remapped anywhere in the problem domain. However, if symmetrical boundary conditions are to be used, only half structure is considered and charge is placed at the center of symmetry by specifying origin of remap at (0,0,0). In this case, the boundary conditions can be assumed to be reflective at the center of symmetry. These boundary conditions, $bxl = -1, bxu = +1, byl = -1, byu = +1, bzl = -1, bzu = +1$, are applied at the extent of three-dimensional problem defined by $xmin, xmax, ymin, ymax, zmin, zmax$. Other alternative could be the case where the whole beam is modeled. The radius of charge can be calculated and the charge can be placed at a distance significantly greater than the maximum of the radius of the charge and the half-width of the beam. The explosive and the column then can be placed on a straight line parallel to x-axis. The orientation of coordinate axes used in the Air3D model is shown in Figure 3.

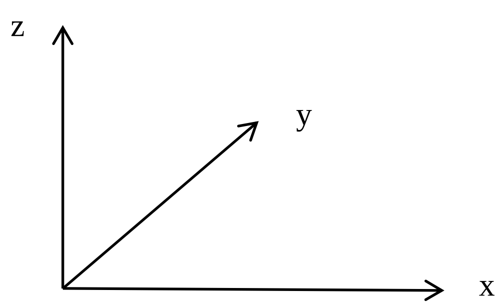

Figure 3: Orientation of co-ordinate axes used in Air3D

In order to avoid boundary effects, the extent of boundaries defined in the problem should always be kept significantly larger than the actual problem definition.

1.3 Analysis procedure

One, two, and three dimensional analyses can be performed with Air3D. The analysis starts with one-dimensional analysis which has a spherical symmetry, and is first-order accurate. First order accuracy is deemed adequate for spherically symmetrical analysis if spatial discretization is sufficiently fine to capture peak responses. Air3D uses the spherical symmetry to model the region of space from the center of charge to the nearest reflecting surface. For the surface burst here, the nearest reflecting surface is the face of the flange of the column, and the distance to nearest reflecting surface is the maximum radius of the spherical analysis. The response quantities are calculated from the spherical analysis. The Euler equations solved for one-dimensional spherical symmetrical analysis are:

$$\mathbf{U}_t + \mathbf{F}_r = \mathbf{S}(\mathbf{U}) \tag{1.1}$$

where $\mathbf{U}_t$ represents the vector of conserved variables, $\mathbf{F}_r$ is the flux vector in the radial direction, and $\mathbf{S}(\mathbf{U})$ are the extra source terms that account for flux contributions due to missing spatial directions. One-dimensional is discretized in equal radial divisions of Δr. As a guide, each radial discretization (or mesh) should represent a scaled radial distance $(= \Delta r / W^{1/3})$ of about $1.0 \times 10^{-3}\ m / kg^{1/3}$. This gives approximately 50 meshes through the radius of explosive charge, which produces very accurate peak pressures from calculations.

One-dimensional analysis is followed by a radially symmetric two-dimensional analysis. The two-dimensional analysis is symmetric about the h (height) axis, and the other coordinate, r, is the radial distance from the axis of symmetry. The two components of velocity are radial velocity, $u(r,h)$, and axial velocity, $v(r,h)$. At the beginning of two-dimensional analysis, the results of one-dimensional analysis are remapped into the computational grid of two-dimensional model. Rest of the model in space is then filled with air at atmospheric conditions. Two-dimensional analysis is performed to obtain the response quantities in axial and radial directions. The Euler equations solved for two-dimensional radially symmetrical analysis are:

$$\mathbf{U}_t + \mathbf{F}(\mathbf{U})_r + \mathbf{G}(\mathbf{U})_h = \mathbf{S}(\mathbf{U}) \tag{1.2}$$

where $\mathbf{G}(\mathbf{U})_h$ is the flux vector in axial direction along the height, and other terms have been defined before. The mesh size of two-dimensional model is usually much larger than one-dimensional analysis, which needs to be established by trial and error. As a guide, one can start with twice the mesh size used for one-dimensional analysis.

At the beginning of three-dimensional analysis, the results of one-dimensional spherically symmetrical analysis and two-dimensional radially symmetrical analysis is remapped into the computational grid of three-dimensional model. Again, remainder of the space in the model is filled with air at atmospheric conditions. The Euler equations solved for three-dimensional radially symmetrical analysis are:

$$\mathbf{U}_t + \mathbf{F}(\mathbf{U})_x + \mathbf{G}(\mathbf{U})_y + \mathbf{H}(\mathbf{U})_z = 0 \tag{1.3}$$

where $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{H}$ are the flux vectors along x, y, and z directions, respectively. Note that there is no additional source term, $\mathbf{S}(\mathbf{U})$, is present in three-dimensional analysis because it considers flux contributions due to all possible directions and there is no missing spatial direction. The size of the mesh used for three-dimensional analysis need to be established by trial and error as well. Four different mesh sizes were used here to obtain the response quantities from three-dimensional analysis. This also helped in understanding the sensitivity of different results to the mesh sizes used in the problem. Since a hemi-spherical surface burst is modeled here, charge mass is doubled because only half of the conserved variables are remapped into the three-dimensional domain.

1.4 Results and discussions

1.4.1 Blast load parameters

The results of Air3D analyses obtained for different mesh sizes are presented in Table 3,

Table 4, Table 5, and Table 6.

Table 3: Results of Air3D analysis (mesh size=10 mm, t=5 msec)

Location No.	Elevation (m)	Peak reflected pressure (MPa)	Specific reflected impulse (MPa-msec)	Arrival time (msec)	Positive phase duration (msec)
1	0.50	70.5	24.1	0.84	2.76
2	1.50	44.4	16.6	0.96	2.63
3	2.50	28.2	9.5	1.19	2.40
4	3.50	15.3	5.4	1.47	2.12
5	4.50	7.6	3.5	1.80	2.07
6	0.50	56.1	18.2	0.84	2.61
7	1.50	35.8	12.4	0.96	2.47
8	2.50	21.1	7.1	1.19	2.24

9	3.50	12.3	4.1	1.48	2.24
10	4.50	6.3	2.7	1.81	2.13

Table 4: Results of Air3D analysis (mesh size=16 mm, t=5 msec)

Location No.	Elevation (m)	Peak reflected pressure (MPa)	Specific reflected impulse (MPa-msec)	Arrival time (msec)	Positive phase duration (msec)
1	0.50	66.1	24.0	0.84	2.82
2	1.50	42.8	16.5	0.95	2.68
3	2.50	26.6	9.5	1.18	2.42
4	3.50	15.1	5.5	1.47	2.13
5	4.50	7.4	3.5	1.80	1.97
6	0.50	53.6	18.8	0.84	2.64
7	1.50	35.6	13.0	0.96	2.50
8	2.50	20.4	7.5	1.18	2.28
9	3.50	12.6	4.4	1.48	2.01
10	4.50	6.4	2.9	1.81	2.15

Table 5: Results of Air3D analysis (mesh size=24 mm, t=5 msec)

Location No.	Elevation (m)	Peak reflected pressure (MPa)	Specific reflected impulse (MPa-msec)	Arrival time (msec)	Positive phase duration (msec)
1	0.50	61.8	23.6	0.83	2.80
2	1.50	40.2	16.3	0.95	2.66
3	2.50	25.0	9.4	1.18	2.43
4	3.50	14.9	5.5	1.47	2.14
5	4.50	7.2	3.5	1.79	1.94
6	0.50	50.4	19.3	0.83	2.69
7	1.50	34.1	13.3	0.95	2.54
8	2.50	19.4	7.7	1.18	2.31
9	3.50	12.8	4.6	1.48	2.03
10	4.50	6.4	3.0	1.81	2.07

Table 6: Results of Air3D analysis (mesh size=32 mm, t=5 msec)

Location No.	Elevation (m)	Peak reflected pressure (MPa)	Specific reflected impulse (MPa-msec)	Arrival time (msec)	Positive phase duration (msec)
1	0.50	56.1	22.6	0.84	2.81
2	1.50	37.1	15.7	0.94	2.66
3	2.50	23.6	9.2	1.17	2.44
4	3.50	14.1	5.3	1.47	2.14

5	4.50	7.0	3.4	1.80	1.93
6	0.50	31.4	12.6	0.84	2.49
7	1.50	22.3	9.0	0.94	2.35
8	2.50	12.6	5.4	1.17	2.13
9	3.50	9.3	3.3	1.48	1.82
10	4.50	4.7	2.2	1.81	2.09

1.4.2 Pressure histories

The response quantities were obtained for four mesh sizes. The pressure histories at the bottom, middle, and top of the column obtained with mesh size 10 mm is shown in Figure 5.

Local spikes are observed in the reflected pressure histories presented in Figure 5. Ideally, there should not be any spikes in pressure-histories as pressure should jump instantaneously and then decay continuously. Appearance of local spikes might be due to the clearing effects from side-faces of the column or the reflection from the domain boundaries specified in the Air3D model. Increasing mesh size reduces the local spikes in the pressure-histories, which is expected because large mesh cannot capture fine variations and smoothen out the response histories.

To investigate the reason for local spikes in the pressure-histories an additional analysis was done in which column is replaced by a continuous solid boundary at the same standoff distance and extending in the whole y and z directions. The mesh was kept the same (10 mm) in both cases. The results obtained from the new analysis were compared with the previous analysis with the regular column. No significant differences were observed, suggesting that clearing effects from side faces do not impact the pressure-histories.

Another analysis was done with domain extended much beyond than the geometry of the column. Again, no differences were observed. So, it can be concluded that even the extent of the boundary was not the cause of the local spikes in the pressure-histories.

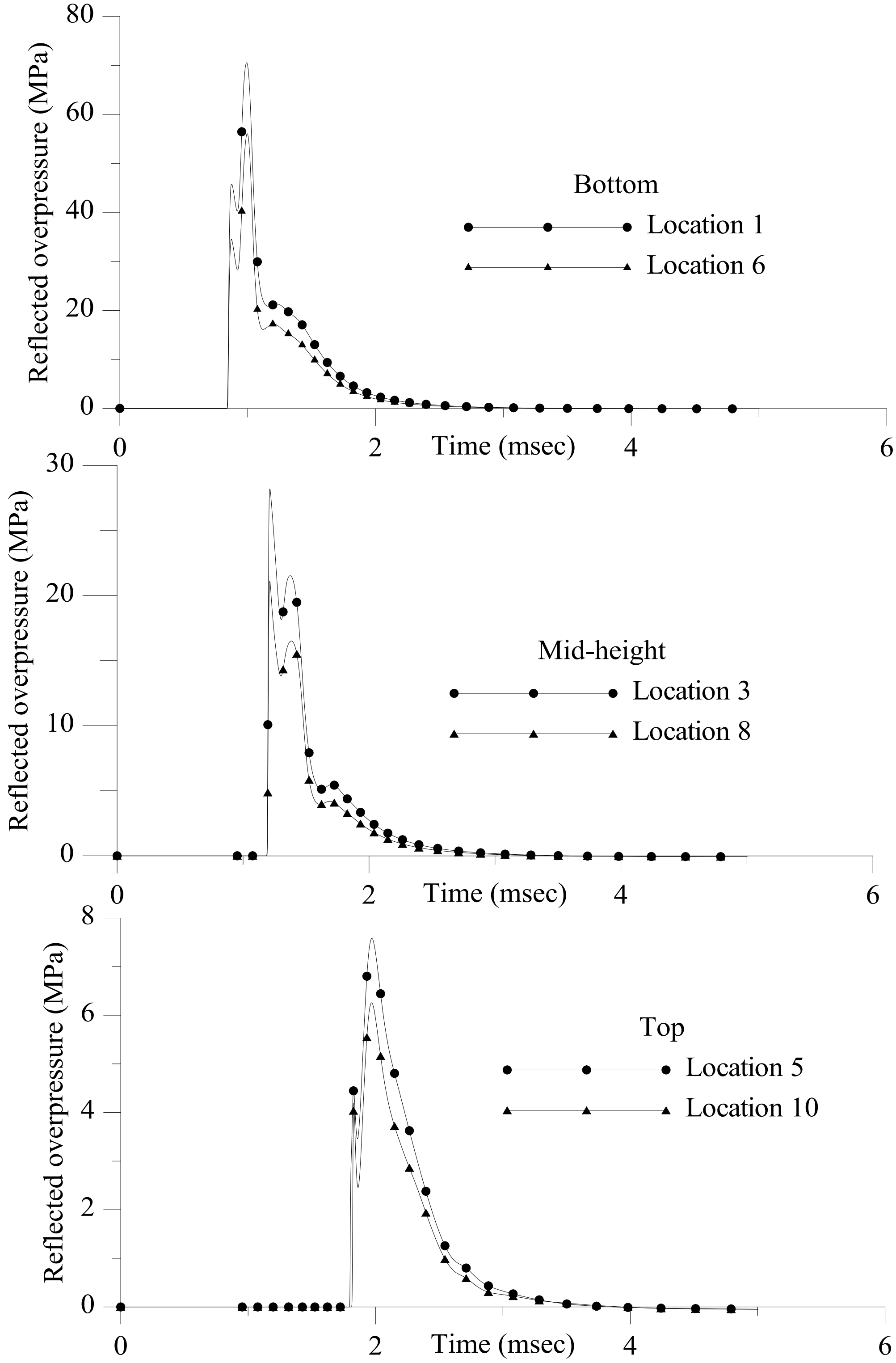

Figure 4: Reflected pressure histories at the monitoring points (mesh=10 mm)

1.4.3 Mesh sensitivity

The overpressure histories and peak reflected overpressures for different mesh sizes are presented Figure 6 and Figure 6.

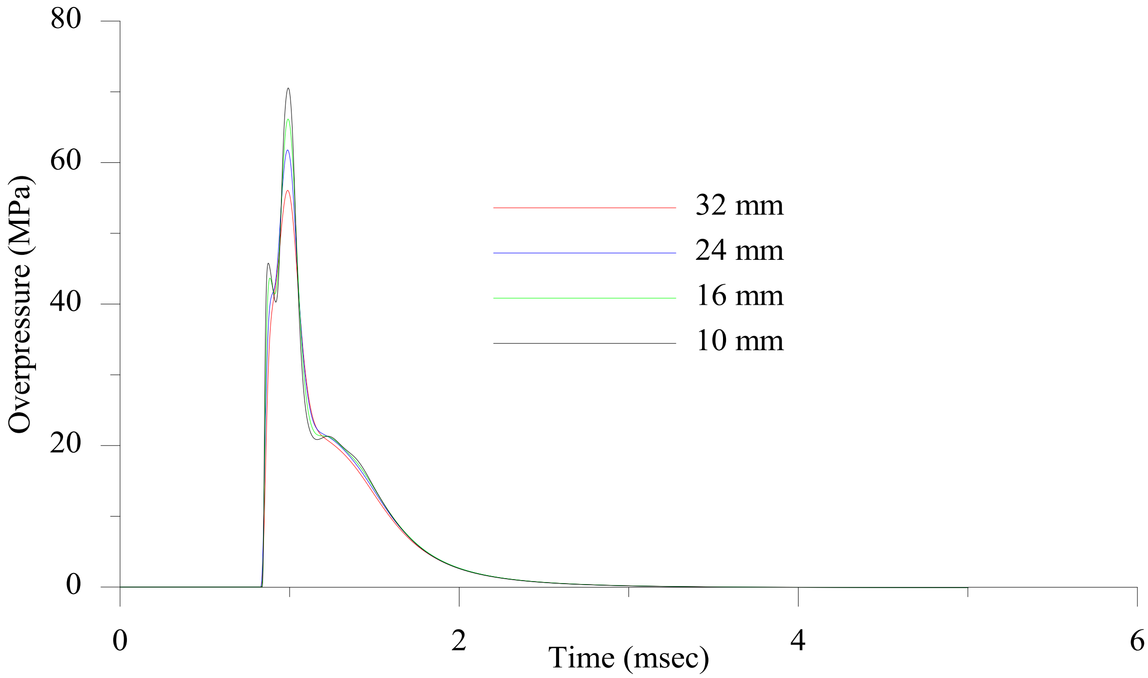

Figure 5: Mesh sensitivity of pressure histories (location 1)

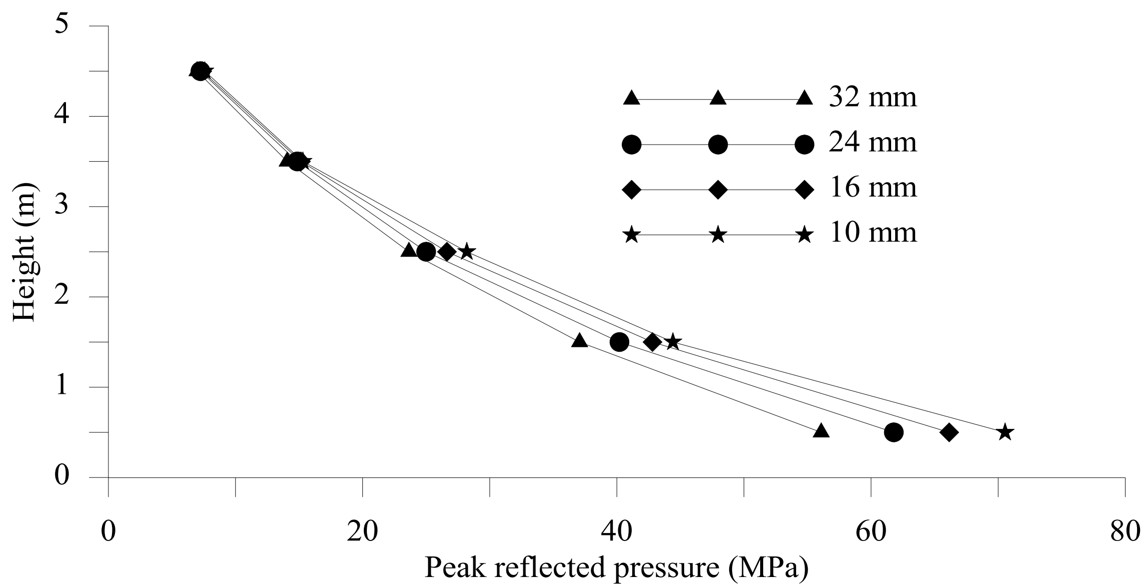

Figure 6: Mesh sensitivity of peak reflected overpressures

1.4.4 Overpressure contours

A screenshot of the contours of blast waves obtained from Air3D at 1.26 msec, 1.99 msec, and 2.47 msec is shown in Figure 7.

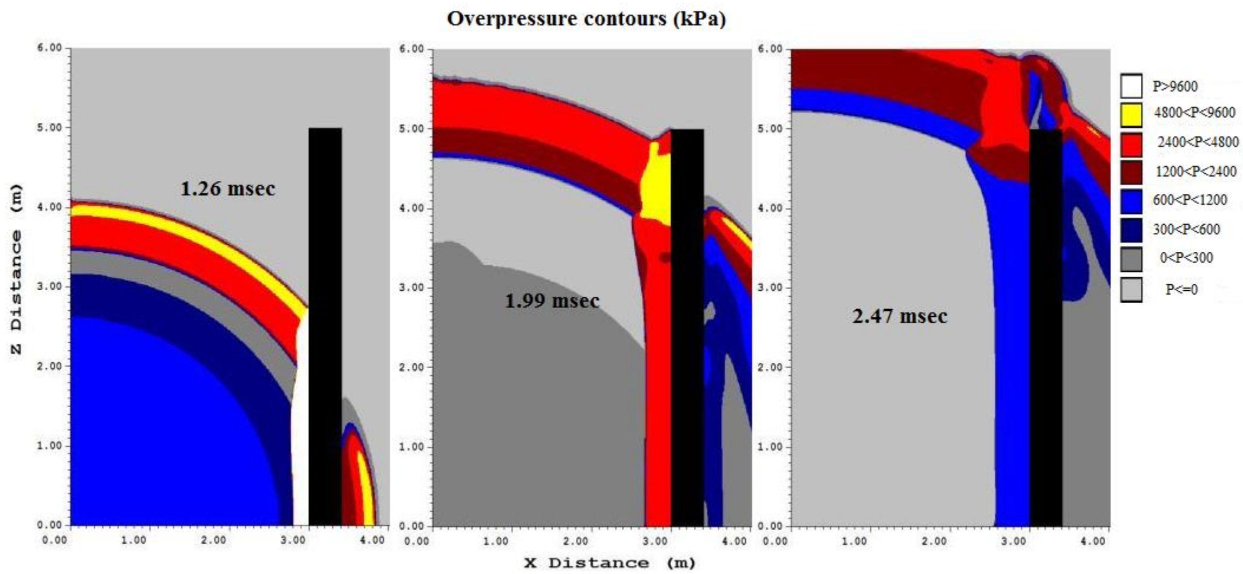

Figure 7: Contours of overpressure at different time intervals (mesh size= 10 mm)

Comparison of blast loading parameters obtained from Air3D (mesh size = 10 mm) and through the charts developed by Biggs (1964), DoD (2008) and PDC-TR-06-01 (2008) is presented in Table 7.

Table 7: Comparison of the results

Location	Peak reflected pressure (MPa)		Specific reflected impulse (MPa-msec)		Arrival time (msec)		Positive phase duration (msec)	
	Charts	Air3D	Charts	Air3D	Charts	Air3D	Charts	Air3D
Base	62	63.3	23.8	21.1	0.8	0.84	4.8	2.68
Mid-height	30	24.6	15.8	8.3	1.2	1.19	11.9	2.32

1.5 Conclusions

The following conclusions are drawn from the surface blast analysis using Air3D:

- Results of Air3D analysis compared reasonably well to that obtained from design charts of DoD (2008) at the base of column. Differences were observed on moving up the height of the column.
- The peak reflected overpressure was sensitive to the mesh size. Value of peak reflected overpressure increased at all monitoring points with decreasing mesh size.
- When the mesh size is increased, the peak reflected pressure is reduced. This might be attributed to inability of models with larger mesh sizes to capture the peak value.
- Apart from the peak value of reflected overpressure, the pressure history was insensitive to the mesh size. Hence, specific reflected impulse, which is the area under pressure-history graph, was insensitive to the mesh size.
- The arrival time and positive phase durations were also insensitive to the mesh size.
- The mesh-sensitivity of peak reflected overpressure obtained from Air3D decreases along the height of the column.

References

Biggs, J. M. (1964). "Introduction to structural dynamics." McGraw-Hill New York.

DoD (2008). "Design of structures to resist the effects of accidental explosions." Report UFC-3-340-02, US Department of Defense, Washington, D.C.

PDC-TR-06-01 (2008). "US Army Corps of Engineers Protective Design Center Technical Report." *Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets*.

Rose, T. A. (2006). "Air3D version 9 users's guide: A computational tool for airblast calculations." Engineering Systems Department, Cranfield University, United Kingdom.

Appendix A

Air3D Input File

```
!-----------------------------------------------------------------------------
---
!
!  E X A M P L E   0 1  ---  B L A S T   W A V E   C L E A R I N G
!
SPHERICAL_INPUT--------------------------------------------------------------
---
!
!___explosive input
!
1.60e+3                       density              (kg/m^3)
4.52e+6                       energy               (J/kg)
6.73e+3                       detonation velocity (m/s)
!
! Reference:
! Baker WE, Cox PA, Westine PS, Kulesz JJ & Strehlow RA
! "Explosion Hazards and Evaluation."
! Elsevier Scientific Publishing Company,
! ISBN 0-444-42094-0 (Vol 5), 1983.
!
!___output remap file
!
0_a1_s08_s.tnt                output file
!
!___charge mass and domain
!
1000.000                      charge mass      (kg)
3.0                           radius           (m)
2.0e-3                        delta r          (m)
!
!___program control
!
0.01                          problem time     (sec)
0.75                          CFL
true                          execution flag
!
!___plotting parameters
!
0.0  100                      display increment (sec) or cycles
1                             plot variable
false                         bitmaps
!
!___target points
!
0 1 noformat static true      no. points, start, reformat, stat/dy, temp_flag
!
RADIAL_INPUT_________________________________________________________________
___
!
!___output remap file
!
0_a1_s08_r.tnt                output file
```

```
0.0                          height of burst (m)
!
!___domain definition
!
5.0e-3                       cell size (m)
3.00                         rmax      (m)
10.0                         hmax      (m)
-1 +1                        boundary conditions, bru, bhu
!
!___program control
!
0.01  false                  problem time (sec), persist
1.0                          switching factor
5.0e-1                       CFL
true                         execution flag
!
!___plotting parameters
!
2                            plot option
1                            plot variable
true                         white background
0.0  100                     display increment (sec) or cycles
2  .001 .001                 ixy, plotlevr, plotlevh
300  0                       scale factor, exponent (shock indicator)
false                        bitmaps
!
!___obstacle definition
!
begin_obstacles
end_obstacles
!
!___target points
!
0 1 noformat static true     no. points, start, reformat, stat/dy, temp_flag
!
MAIN_INPUT------------------------------------------------------------------
!
!___input remap file
!
radial                       file type
0.0  0.0  0.0                origin of remap x,y,z (m)
!
!___domain definition
!
!
10.0e-3                      cell size  (m)
0.0   5.0                    xmin, xmax (m)
0.0   1.0                    ymin, ymax (m)
0.0   6.0                    zmin, zmax (m)
-1 +1 -1 +1 -1 +1            bxl,bxu, byl,byu, bzl,bzu
!
!___program control
!
0.005  false                 problem time (sec), persist
1.0                          switching factor
5.0e-1                       CFL
!
```

```
!___plotting parameters
!
2                             plot option
1                             plot variable
true                          white background
0.0       50                  display increment (sec) or cycles
300  0                       scale factor, exponent (shock indicator)
2  .001 .001 .001             ixyz, plotlevx, plotlevy, plotlevz
false                         right hand rule
true                          bitmaps
true                          vrml_flag
true                          vrml_windows
true                          vrml_average_pressure
true                          vrml_gauges
!
!___obstacle definition
!
begin_obstacles
cuboid 3.0000 3.4160 0.0000 0.2030 0.0000 5.0000 false
end_obstacles
!
!___windows and average pressure regions
!
0                             no. of window types
0 1 0 noformat                no. of windows, start, cells contained, format
flag
0 1 0 noformat                no. of ave pressure zones, start, cells, format
flag
!
!___target points
!
10 1 reformat static false    no. points, start, reformat, stat/dy, temp_flag
3.000 0.015 0.500
3.000 0.015 1.500
3.000 0.015 2.500
3.000 0.015 3.500
3.000 0.015 4.500
3.000 0.195 0.500
3.000 0.195 1.500
3.000 0.195 2.500
3.000 0.195 3.500
3.000 0.195 4.500
```