BLAST PROTECTION USING PERIMETER WALLS

by

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ABSTRACT

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The impact of a blast scenario is studied by many researchers and the different estimation techniques and design manuals are developed for designing against blast loads. Conducting experiments and using empirical formulae are the two methods for this estimation. The third method is the use of the computational fluid dynamics tools for the calculations to obtain the peak pressures on a blast. In this study, one of those tools, Air3D, is used to determine the reflected pressures as well as impulses for different geometries. Two measures to take to reduce the impact of an explosion are using blast walls and increasing the distance to the blast. The main purpose of this study to have a parametric study on both using the Air3D tool. Validation of the tool is made by comparing the results with the results of an experiment which is available in the literature and also with the readings of the design charts. Also, a sample design is made for the blast wall using design charts and procedures to make sure the wall stays in place after the blast. Then, the parametric studies are conducted with four different wall heights and four different wall to building distances as well as no wall cases. The results show that the increase in wall-building distance increase the protection, but in a decreasing trend. When the wall heights are considered, it is seen that blast walls protect the structures in low heights, especially along their heights, but may cause higher pressures in higher points of the structure.

ÖZET

ÇEVRE DUVARLARI KULLANILARAK PATLAMAYA KARŞI KORUMA SAĞLAMA

Bir patlama senaryosunun etkileri birçok araştırmacı tarafından çalışılmış ve patlamaya karşı dizayn konusunda çeşitli tahmin teknikleri ve yönetmelikler geliştirilmiştir. Bu tahminlere ulaşmak için iki yöntem, deneyler yapma ve ampirik formülleri kullanmaktır. En yüksek basınç değerlerini bulmak için üçüncü bir yöntem ise akışkanlar mekaniği kuralları ile oluşturulmuş programları kullanımıdır. Bu çalışmada en yüksek basınç ve itki değerlerini hesaplamak için bahsedilen programlardan biri olan Air3D kullanılmıştır. Patlamanın etkisini azaltacak iki önlem, patlama duvarı kullanımı ve patlamaya olan mesafenin artırılmasıdır. Bu çalışmanın ana hedefi, Air3D kullanılarak bu ikisi üzerine parametrik bir çalışma yapılmasıdır. Programın sonuçlarının onaylanması için literatürde yer alan bir deneyin sonuçlarının ve dizayn grafiklerinden elde edilen verilerin Air3D sonuçları ile karşılaştırması yapılmıştır. Aynı zamanda patlama duvarının patlama sonrası ayakta kaldığından emin olmak için dizayn grafikleri ve şartnameleri kullanılarak örnek bir patlama duvarı tasarımı yapılmıştır. Daha sonra dört farklı duvar tipi, dört farklı uzaklık ve aynı zamandı duvarsız durumlar düşünülerek parametrik çalışmalar yapılmıştır. Sonuçlar gösteriyor ki, duvar ve bina arasında mesafe arttıkça koruma armakta, fakat azalan bir eğilimde artmaktadır. Duvar yükseklikleri incelendiğinde ise patlama duvarlarının düşük yüksekliklerde, özellikle kendi yüksekliklerinde binaya koruma sağladıkları ama binanın yüksek noktalarında daha yüksek basınç değerlerine de sebep olabilecekleri görülmektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A_{gv}	Shear reinforcement area
A_s	Reinforcement area
b	Width of section
d_c	Effective depth
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel
$f_c^{'}$	Concrete strength
$f_{dc}^{'}$	Dynamic pressure strength of concrete
f_{du}	Design ultimate strength
f_{dy}	Design yield strength
f_y	Reinforcement yield strength
f_{yv}	Shear strength of reinforcement
H	wall height
h_e	height of blast
I	Moment of inertia
i_r	Reflected impulse
K_{LM}	Equivalent load-mass factor
M_n	Moment capacity
n	The ratio of modulus of elasticity for reinforcement steel to modulus of elasticity for concrete
P_0	Atmospheric pressure
P_{min}	Minimum pressure
P_{max}	Peak pressure
P_r	Peak reflected pressure
R	Distance to an explosion
r_u	Unit resistance to bending
s	Reinforcement spacing on both sides
s_v	Shear reinforcement spacing
t	Total thickness

T_s	Positive wave duration
t_m	Time needed to reach the maximum displacement
t_A	Arrival time of the shock wave
t_P	Duration of the positive phase
t_N	Duration of the negative phase
v_u	Ultimate shear stress
v_c	Shear capacity
W	Charge weight
X_m	Maximum displacement
Z	Scaled distance
ϕ	Reinforcement diameter
ρ_c	Concrete density
ρ_s	Longitudinal reinforcement percentage

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
ANFO	Ammonium nitrate-fuel oil
AUSM	Advection Upstream Splitting Method
CFD	Computational Fluid Dynamics
FEMA	Federal Emergency Management Agency
PETN	Pentaerythritol tetranitrate
TNT	Trinitrotoluene

1. INTRODUCTION

Impacts of accidental explosions or blast attacks is a crucial matter of the subject, especially for high importance buildings. The impacts of blasts on the buildings have been studied in terms of peak pressures and impulses. When protection is needed, using blast walls and increasing the distance to an explosion are the two most common protection measures.

In an explosion, blast waves occur and propagate. As the wave propagates, it losses energy. Hence, increasing the distance to the explosion decreases the effect. Similar reduction occurs when there is a blast wall since the wave has to travel above the wall in that case.

When a pressure wave hits a surface, it creates a higher pressure than the free air blast case. This higher pressure is called reflected pressure. In the design against blast loads, these reflected pressures are considered. However, considering only peak reflected pressures is not adequate. The duration of the pressure also should be considered. The indicator of this effect is the impulse, which is obtained by integrating the pressure with respect to time.

When a blast wall is present, five parameters are involved that changes the effect of a blast. These are charge weight, height of burst, distance from charge to wall, distance from wall to structure and wall height. In this thesis, parametric studies on both wall height and wall-building distance are conducted. These two parameters are combined and analyzed in different simulations.

A computational tool called Air3D v9 is used to obtain the reflected pressures on a predefined building for different cases. Then the corresponding impulses are extracted and compared to get a combined effect of wall-building distance and wall height on a structure.

Air3D is a fluid dynamics solver, created by Dr. Timothy A. Rose to use in airblast calculations. The program is based on the finite volume approach. It can solve problems in one, two or three dimensions. It uses Euler equation forms on a typical Cartesian grid. The solution method is a version of Advection Upstream Splitting Method: AUSMDV [13]. Besides, if used in two or three dimensions, it utilizes the MUSCL-Hancock time integration [14].

The main aim of the study is to validate the tool Air3D and use it for different cases of geometries to have a parametric study for a car bombing scenario, to discuss the effectiveness of both blast wall height and wall-building distance, and also present the protection provided by them. Additionally, these simulations could be used to estimate real-life impulses for similar structures and scenarios, since the tool is validated.

2. LITERATURE REVIEW

A blast wall is a wall which protects the structure against the impacts of an explosion. In an explosion, an extreme amount of energy is transferred in the air as a wave. When this wave reaches a structure it impacts the surface and reflects. Due to this reflection, a reflected pressure load is applied to the structure. After this reflection, pressures drop in a short time exponentially and goes to the negative phase, meaning it creates a vacuum [1]. This ideal blast wave can be seen in Figure 2.1.

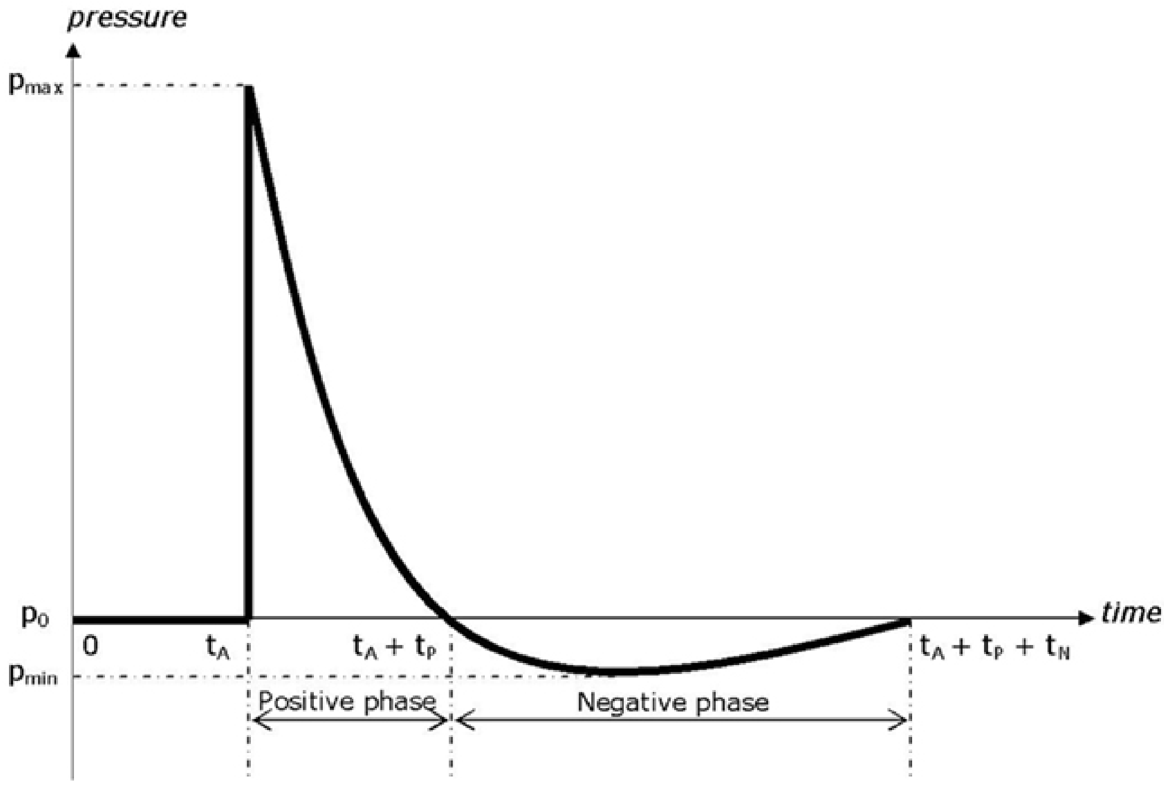


Figure 2.1. Ideal blast wave [1].

In Figure 2.1, P_{max} represents the peak pressure, P_0 represents the atmospheric pressure, P_{min} represents the minimum pressure in the negative phase, t_A represents the arrival time, t_P represents the positive phase duration and t_N represents the negative phase duration.

The peak pressure is an important measurement, however, the duration of the effecting pressures should also be considered while inspecting blast effects. Therefore, impulses on structures also needed to be examined. The resulting impulses are calculated by taking the integral of the pressure with respect to time [1].

Effects of the blast mainly depend on the distance to the explosion and the weight of the charge. It is stated in the Hopkinson's Law that these two variables are correlated, such that any pressure caused by an explosion in a distance R_1 and a charge weight W_1 can be achieved with any distance R_2 and charge weight W_2 within the same atmosphere and with the same charge geometry as long as the following equation holds [1]:

$$\frac{R_1}{R_2} = \left(\frac{W_1}{W_2}\right)^{\frac{1}{3}} \tag{2.1}$$

That is why a scaled distance, Z is used in the equations.

$$Z = \frac{R}{W^{\frac{1}{3}}} \tag{2.2}$$

Baker [1] provides design charts to get the pressures using these scaled distance value. These charts are presented and used in Chapter 3.

A blast wall has two advantages in protection against blast. One of them is blocking the way created by the blast. Thus, a shadow zone is created behind the wall for protection. This shadow effect can be seen in Figure 2.2 [2]. The other advantage is that it provides a standoff distance for the structure. In other words, a threat cannot pass the blast wall so, the distance from the threat to the structure is kept.

The shadow zone does not mean that the point in this zone is free of impact. The wave does not propagate in a linear vector movement. The released energy from an explosion compresses the air and then the air tries to expand in every possible direction similar to fluid flows. Then, the wave creates a vortex at the top of the blast wall and

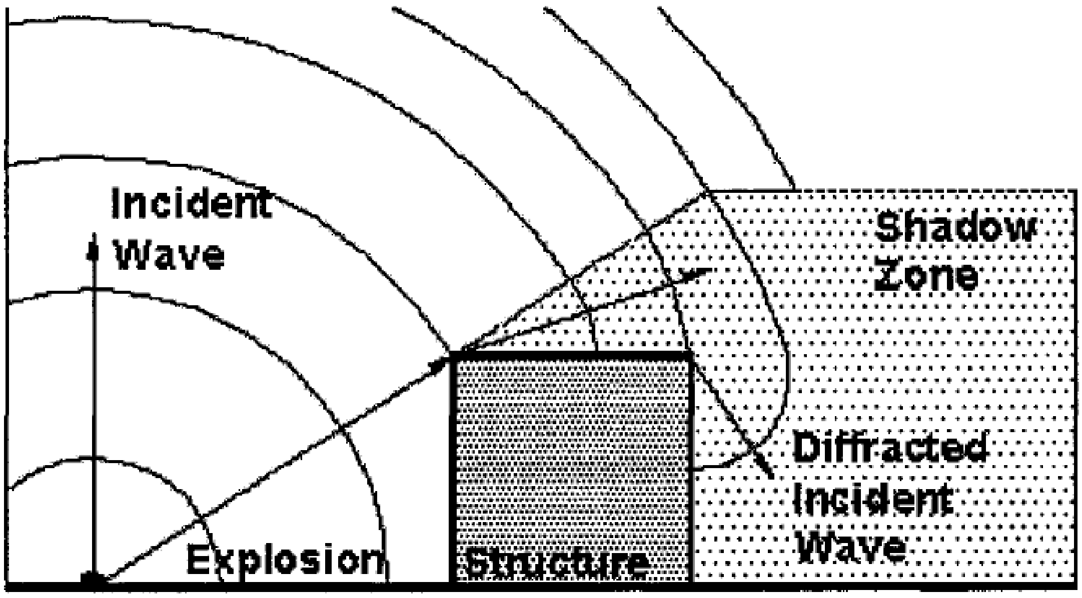


Figure 2.2. Shadow zone created behind a structure [2].

continues the movement in every direction as it is seen in Figure 2.3. In this figure, the movement of the shock wave is sketched [3].

As the wave passes over the blast wall, it continues to propagate in every direction. Thus, part of the wave directly moves towards the structure or measurement point, another part of the wave is directed towards the ground and reflects from the ground and again reaches structure or measurement point.

Depending on the distance and the height of the measurement point, these two ways may create two different peaks in pressure time history or they may create a combined peak. Again, if a structure is present, these waves reflect from the structure and again blast wall, creating other peaks especially if the structure is close to the blast wall. Thus, these interactions create a complex problem that is currently solved with enhanced tools.

There are three different methods to estimate the blast loads. The first of them is the experiment. Experiments can be designed and scaled as needed. Furthermore,

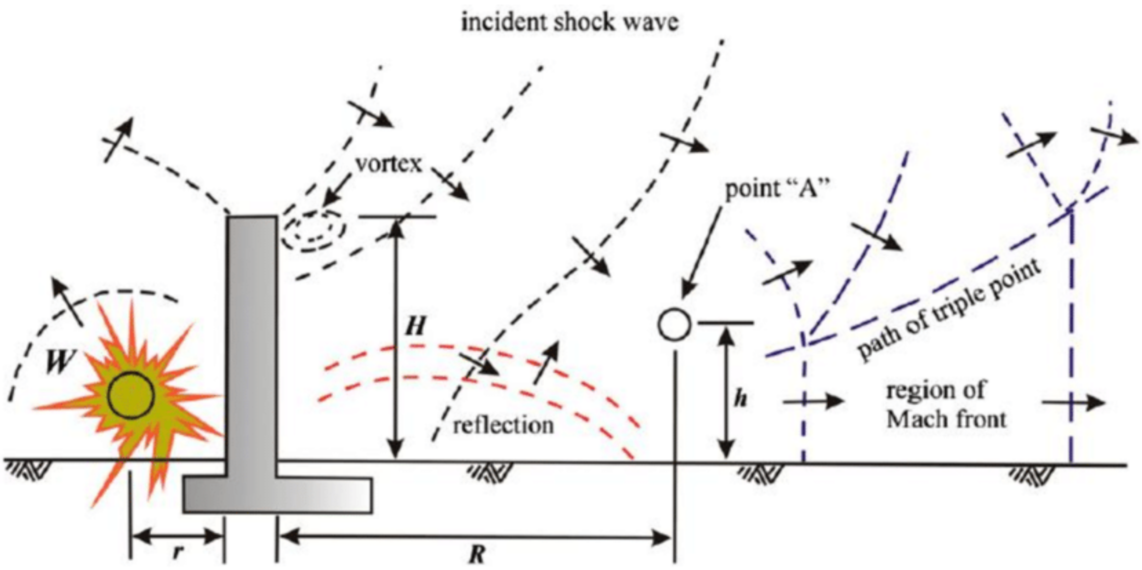


Figure 2.3. Blast Wave Movement in Case of a Blast Wall Present [3].

the results of the small-scale experiments coincide with the full-scale ones.

The study by D. L. Rice [11] is a good example. In that study, a small scale (1:91) version of the full-scale experiments was conducted in New Mexico. Here, the scale was chosen considering the limitations like available charge weights portions, Cranz-Schardin camera view and so on. Consequently, the study presented a good match. The downsides to the blast experiments can be the lack of repeatability and expense. Also, they cost a lot of time and man-power.

Another approach to estimation is the use of empirical or semi-empirical methods. These basic methods are quite handy for preliminary design. However, these methods are usually based on free air explosions, so they can not represent the interaction with other structures or reflections from other surfaces. Most of them are obtained using the experiments of UFC 3-340-01 [15] and presented in several design reports and manuals.

The UFC 3-340-02 [10] manual is one of the most popular ones for design against blast loads. It is again developed after UFC 3-340-1 [15]. Also, CONWEP [16] is another program created using the curves and equations in UFC 3-340-1 [15] and UFC

3-340-2 [10] to predict the effects of a blast.

The last approach is to use computational fluid dynamic models. These models use conservation of mass, energy, and momentum. Most common tools are LS-DYNA, AUTODYN, ProSAir, and Air3D. In the current study, the Air3D solver is used. The disadvantages of these models can be the time to learn the usage and model, long simulation times and the time to post-process.

2.1. Studies With Blast Walls

Rose *et al.* conducted a series of 1:10 scale experiments [4]. There is a wall between the measurement points and blast. Gauges are placed on a grid of three wall heights above the ground and six wall heights behind the wall.

Then the peak pressures and scaled impulses are compared(Figure 2.4). It is concluded that in the observed area behind the wall, pressures and impulses are reduced, but the limits for reduction are 60% and 80% respectively. Also, the reduction amount decreases with the increase in the distance.

Absil *et al.* presented a paper about the effectiveness of the blast walls [17]. The main objective of this study is to reduce the noise level of the army facilities. The authors made laboratory scale shock tube tests and also measurements on army field with 1:10 models. Both a screen and a hike is tested. Besides, they have used TOMAS (a model for acoustic sound diffraction) and BLAST(a fluid dynamics code).

As a result of the study, it is seen that TOMAS overpredicted the reduction by the walls. On the other hand, BLAST code matched the experiment well. Also, it is seen that in close distances, the screen was better at reducing the noise level. However, not to harm the gun personnel, the use of hike was preferred. It is seen that in large distances, the wall geometry did not cause a clear difference.

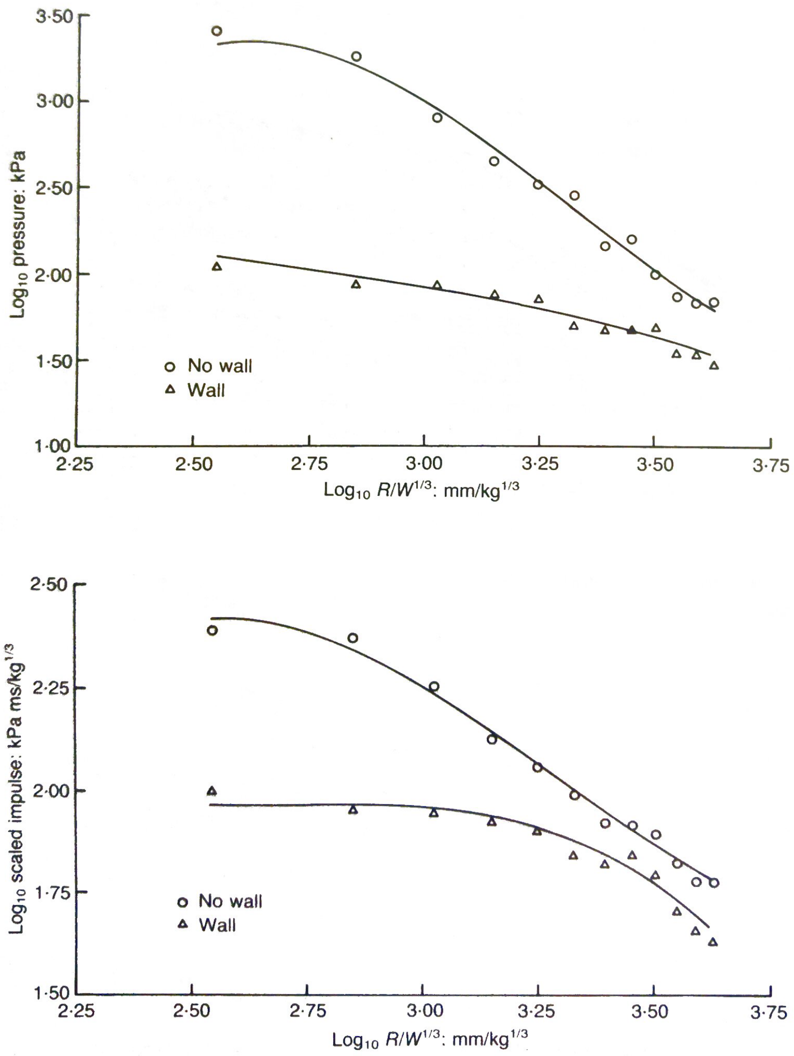


Figure 2.4. Comparison for with and without blast wall cases [4].

Rose *et al.* made some experiments again with different types of walls on 1:10 scale [5]. The configurations, as well as materials of the walls, are changed for tests. Walls were made using a variety of materials like sand monoliths, sand wrapped in geotextile, wood, water, and plastic. Some of those with sand wrapped in geotextiles are constructed in a zig-zagged geometry like seen in Figure 2.5. The walls are constructed to have just enough robustness to be able to remain in place.

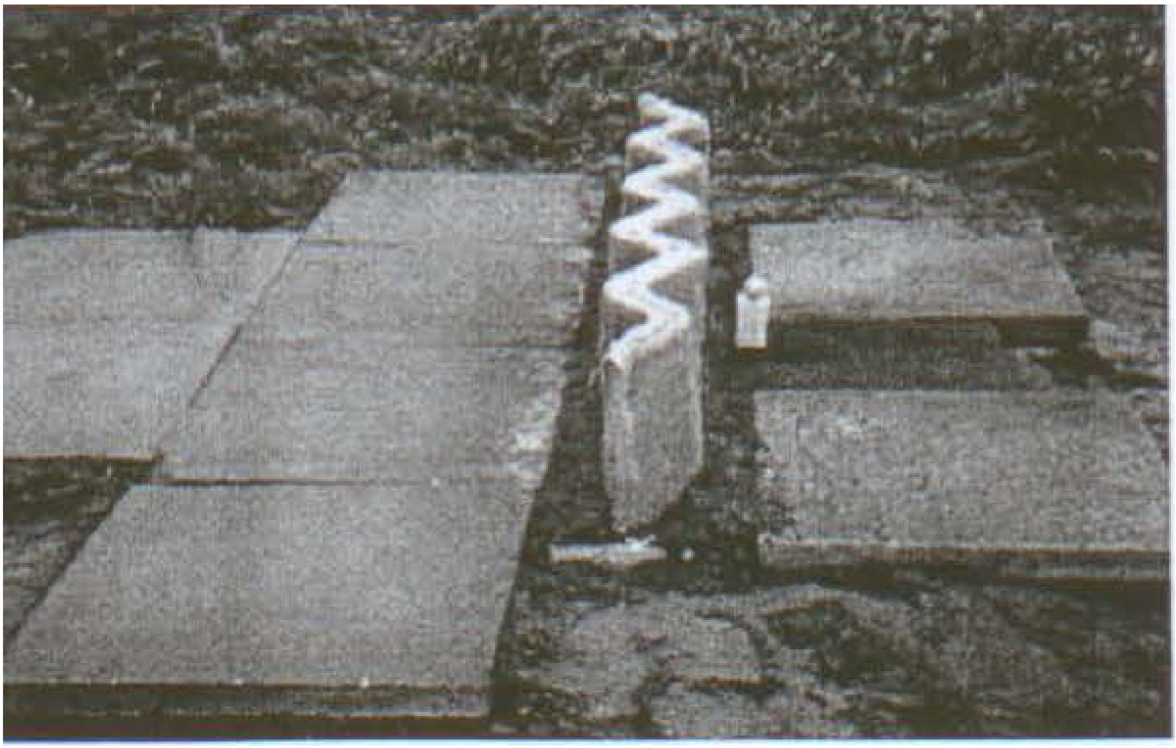


Figure 2.5. Zig-zagged wall used in the experiments of Rose *et al.* [5]

The results of the experiments are compared with no wall case as well as plane steel case(rigid) from previous studies. It is stated that in almost every case, the reduction in the pressures and impulses was as good as the reductions for the cases with undeforming walls, but also stated that heavier walls perform better at reducing the effects of the blast. Finally, it is concluded that for quick solutions non-permanent structures can provide a high degree protection [5].

Rose *et al.* also conducted a variety of experiments with vertical cantilever walls positioned at different horizontal distances between scales from 1:8 and 1:14, and made detailed measurements [6]. Also, the detonation heights for experiments were changing. Peak side-on pressures and impulses are then recorded and used in plots. Then design charts are presented for different scenarios(as seen in Figure 2.6), to provide a simple method to get the side-on pressures and impulses for designing against blast load in case of a present blast wall.

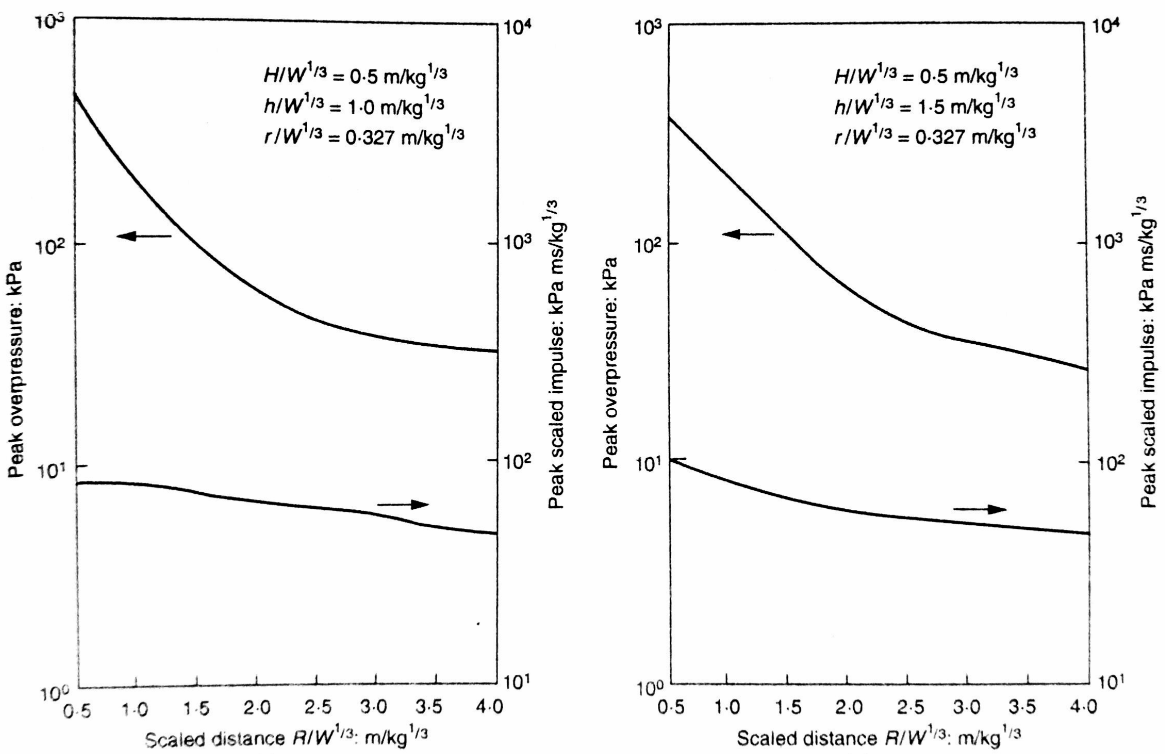


Figure 2.6. Design Curves for Peak Side-on Pressure and Impulse [6].

Zhou and Hao [7] have made some numerical simulations using AUTODYN3D. The purpose of the study was to generate some formulae to predict the peak reflected pressure and impulse behind a wall. It is stated that when these formulae provide a good estimation when it is used with available empirical methods(which are currently used for cases without a wall). In Figure 2.7 an example is presented with no barrier, numerical results and simplified the result.

Xiao *et al.* presented a study with a different wall configuration [8]. In the study, an experiment and some analyses were conducted to see the effect of a metal sheet at top of the blast wall("canopy") as in Figure 2.8. 45 degrees orientations were analyzed.

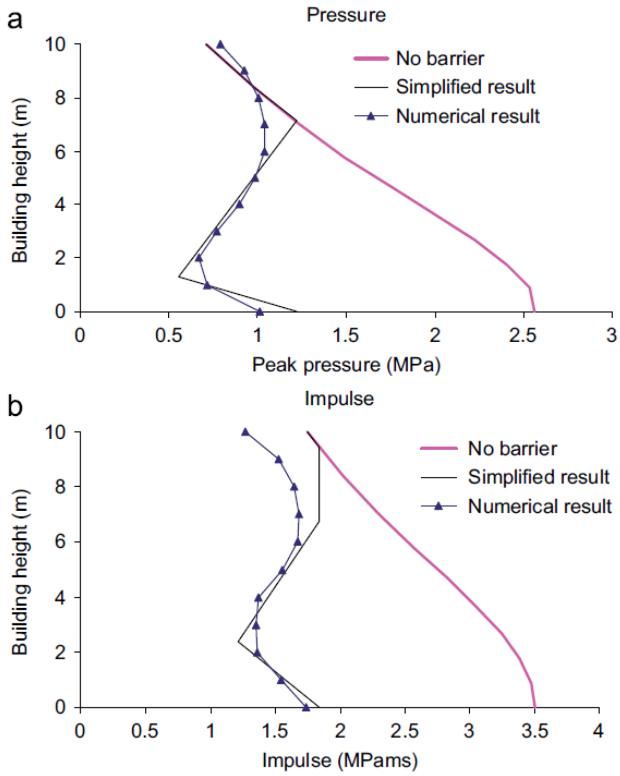


Figure 2.7. Comparison of numerical method and simplified formulae [7].

Also, flexible and rigid canopy options were considered and it was stated that in these case studies the assumption of a rigid canopy was appropriate. It was concluded that some arrangements of the canopy could result in an increase in the reduction of the peak pressures, yet some other positions had an adverse effect.

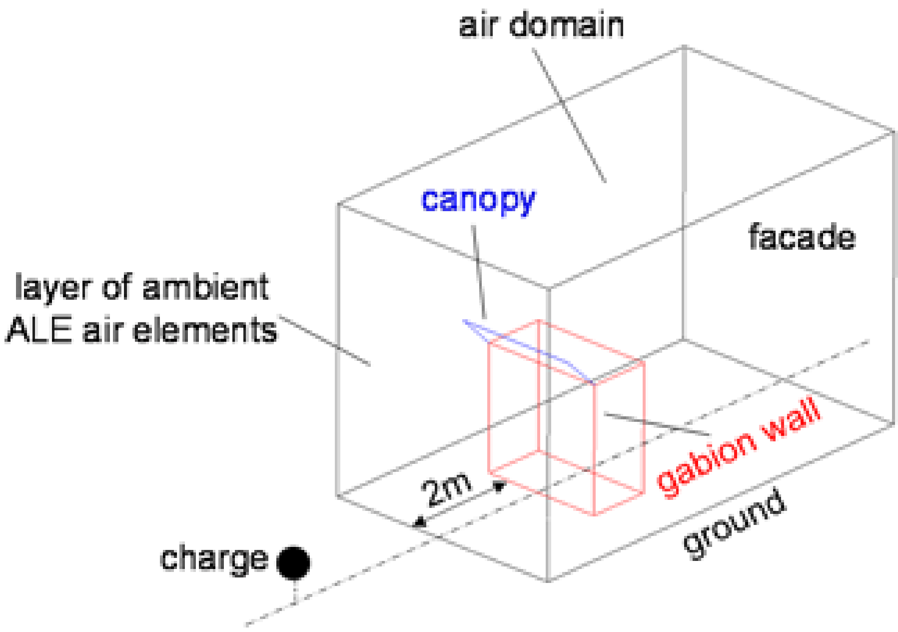


Figure 2.8. A sketch of the numerical model [8].

Chapman *et al.* also conducted some approximately 1:10 scale experiments [18]. In these experiments, different geometries, charge weights and heights of bursts were tested. Measurements were taken behind the wall at a target structure. The aim of this study was to develop a prediction method to obtain the peak reflected pressures and impulses on a structure. As a result, they suggested a method that was used with the "protection factor" which is a modified version of the scaled distance, to predict those values.

In the current study, the effects of the wall to building distance and wall height distance in the protection of a building behind a blast wall were examined. The study was conducted using computational fluid dynamics tool Air3D. Therefore, the building and the blast wall was assumed to be rigid. The necessary calculations were made to make sure the blast wall remains in place. There was no experiment conducted, however, the results of the Air3D were verified with a previous experiment available in the literature. In the analyses, the combined effects of different wall-building distances and wall heights were presented in terms of reflected pressure and impulse. Thus, the results obtained in this study would be the real pressure and impulse values experienced on the façade of the building in case of a similar explosion.

3. BLAST WALL DESIGN

Air3D tool allows only rigid obstacles. Therefore, the blast wall should withstand the blast load used. In this study, a TNT weight of 150kg is used (explained in chapter 5). Thus, before conducting the analyses on Air3D, it should be clear that the blast wall can withstand the impact of the blast.

In this chapter, required reinforcements and the required thickness for the wall is calculated. Air3D tool is used to get the pressure values on the wall. To observe the behavior of the wall, considering only peak pressure values is not adequate. The change in pressure over time is also important. Impulse is the integration of the pressure over time. The blast design codes, use this impulse value in their calculations. Thus, the impulses are also calculated using the Air3D outputs. These calculated impulses and peak pressures were also compared with the impulse and peak pressure read from the charts [1]. Mentioned charts are actively used in design processes to get peak pressure, impulse, time of arrival etc.

3.1. Design for Bending

The sketch of the design problem is represented in Figure 3.1. The values used for the design are summarized below:

- Protection category 2
- Explosive amount, W = 150kg TNT
- Height of blast, h_e = 2m
- Distance between the blast and the wall, R = 2m
- Wall height, H = 5m
- Concrete strength, $f_c^{\prime}$ = 30MPa
- Concrete density, ρ_c = 2400kg/m^3

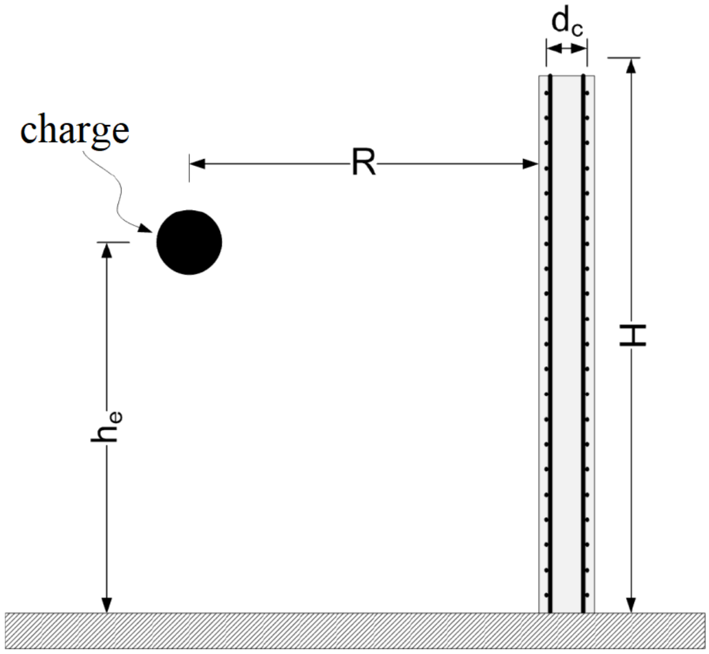


Figure 3.1. Blast wall design sketch. [9]

- Concrete modulus of elasticity(ACI-318, 2008),

$$E_c = 0.043\rho_c^{1.5}\sqrt{f_c'} = 0.043(2400)^{1.5}\sqrt{30} \cong 28000MPa = 28GPa \qquad (3.1)$$

- Reinforcement yield strength, f_y = 450MPa
- Longitudinal reinforcement percentage, ρ_s = 0.5
- Reinforcement spacing on both sides, s = 0.15m
- Reinforcement modulus of elasticity, E_s = 200GPa
- Reinforcement clear cover 0.05

The first step is the calculation of the scaled distance, Z.

$$Z = \frac{R}{(W)^{\frac{1}{3}}} = \frac{2}{(150)^{\frac{1}{3}}} = 0.3764m/kg^{\frac{1}{3}} \qquad (3.2)$$

Using the calculated Z value, scaled reflected impulse, $\frac{i_r}{(W)^{1/3}}$ and scaled positive pressure wave duration, $\frac{T_s}{(W)^{1/3}}$ is read from the charts (Figure 3.2 and Figure 3.3 respectively) as 1900 $Pa.s/kg^{1/3}$ and 0.00021 $s/kg^{1/3}$. Therefore, the calculated reflected impulse is,

$$i_r = 1900(W)^{1/3} = 10095Pa.s. \tag{3.3}$$

Also, the positive pressure wave duration is,

$$T_s = 0.00021(1000)(W)^{1/3} = 1.11ms. \tag{3.4}$$

Next, the strength of materials is calculated using correction factors for dynamic impact.

Reinforcement steel yield strength(f_{dy}), ultimate strength(fdu) and dynamic pressure strength of concrete($f^{'}_{dc}$) is calculated [19].

$$f_{dy} = 1.2(f_y) = 1.2(450MPa) = 540MPa \tag{3.5}$$

$$f_{du} = 1.05(f_u) = 1.05(650MPa) = 680MPa \tag{3.6}$$

$$f_{ds} = f_{dy} + \frac{(f_{du} - f_{dy})}{4} = 540MPa + \frac{680MPa - 540MPa}{540MPa} = 575MPa \tag{3.7}$$

$$f^{'}_{dc} = 1.1(f_c = 1.1(30MPa) = 33MPa \tag{3.8}$$

Then, the moment capacity, M_n, for unit width in terms of effective depth, d_c, is calculated. Effective depth is the distance between reinforcements on both faces of the

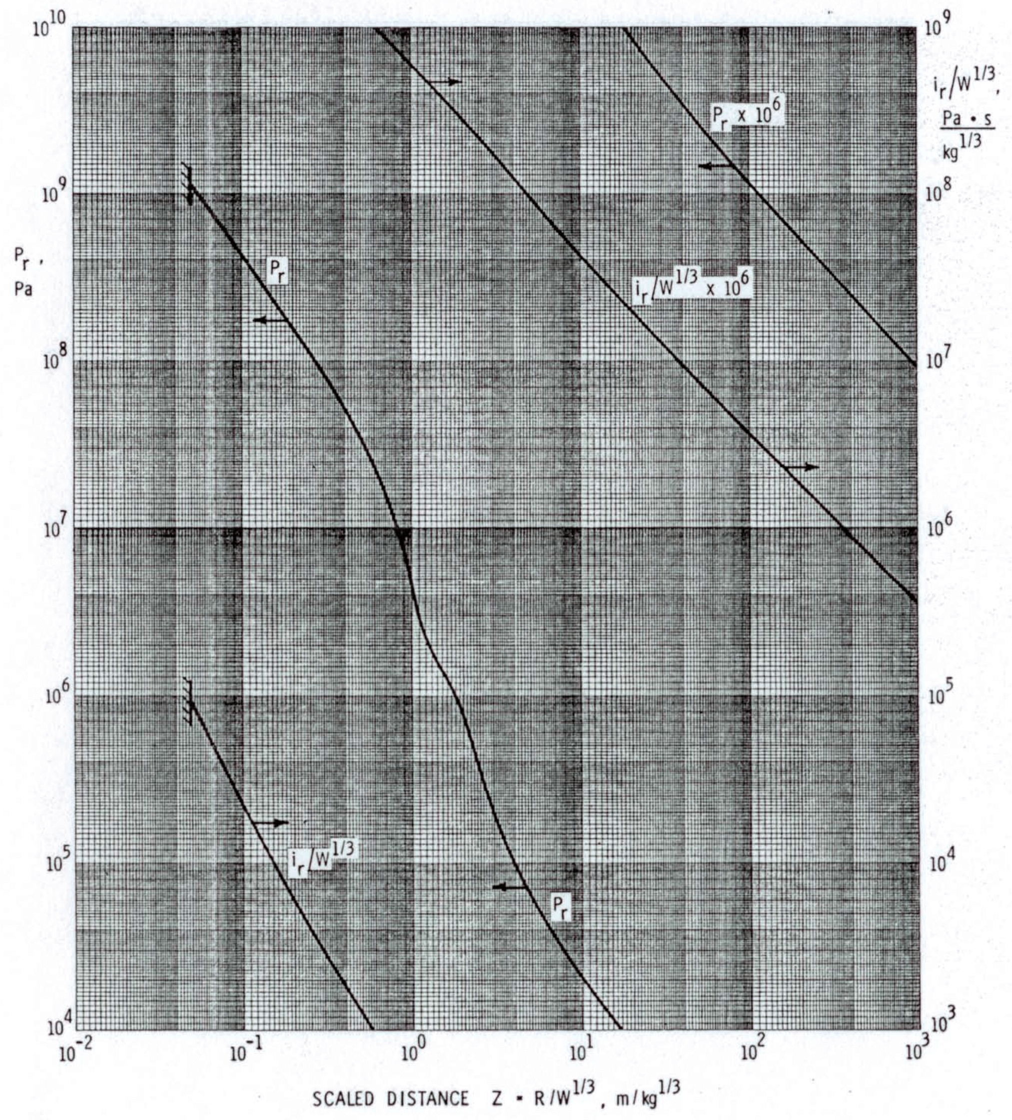


Figure 3.2. Scaled reflected impulse - scaled distance diagram [1].

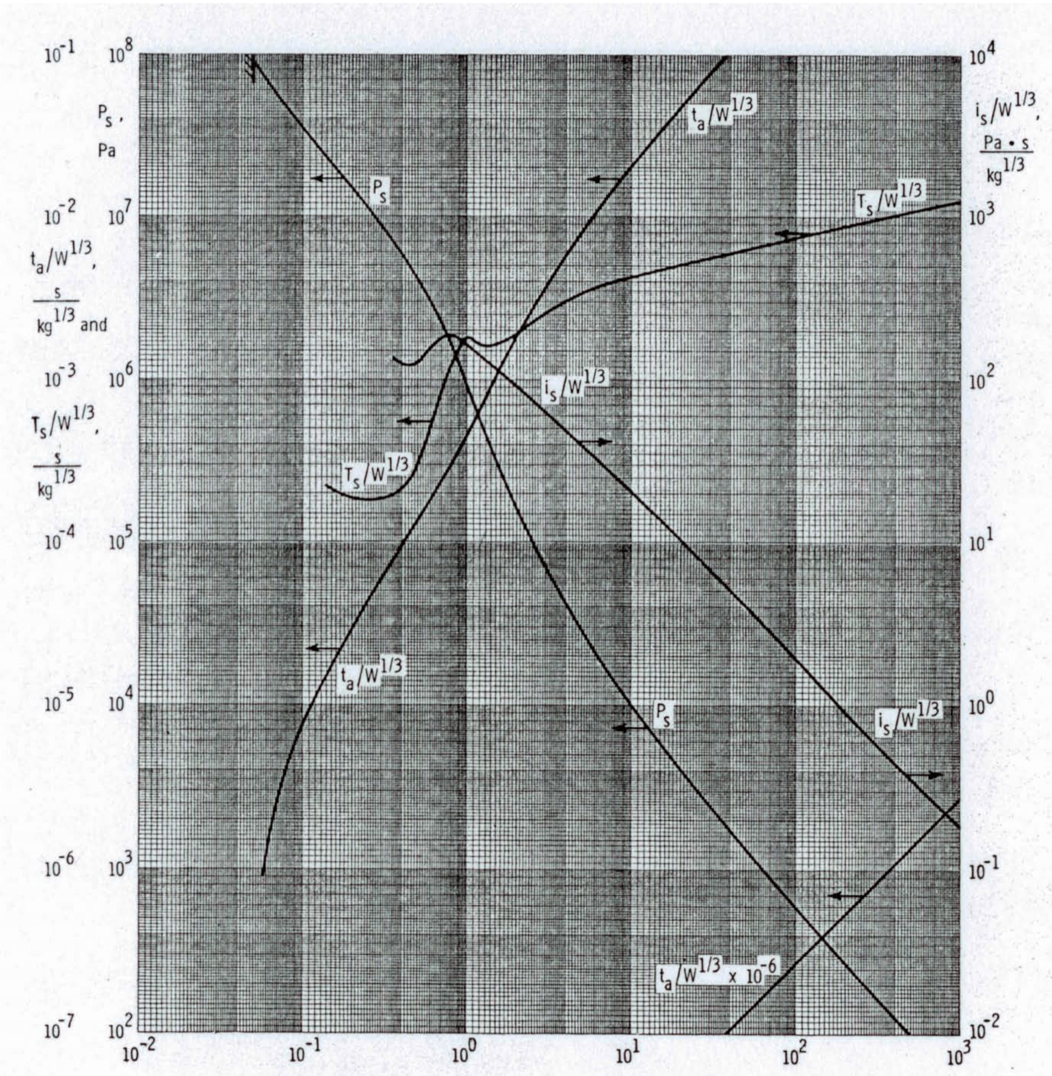


Figure 3.3. Scaled positive pressure wave duration - scaled distance diagram [1].

wall.

$$M_n = \frac{A_s(f_{ds})}{b}(d_c) = (\rho_s)(f_{ds})(d_c)^2 = 0.005(575)(10^6)(d_c)^2 N.m/m \tag{3.9}$$

where, A_s is the total reinforcement area in unit width. Unit resistance to bending (r_u) is calculated using UFC-340-2 specification [10] and in terms of effective depth, d_c.

$$r_u = \frac{2(M_n)}{H^2} = \frac{2[0.005(575)(10^6)(d_c)^2]}{5^2} = 230250(d_c)^2 N/m^2 \tag{3.10}$$

For protection category 2, allowed maximum rotation is 4 degrees. At 4 degrees, maximum displacement of wall calculated geometrically as follows:

$$X_m = Htan(4°) = 0.35m \tag{3.11}$$

The ratio of modulus of elasticity for reinforcement steel to modulus of elasticity for concrete, n is calculated:

$$n = \frac{E_s}{E_c} = \frac{200}{28} = 7.14 \tag{3.12}$$

Using this ratio and the ratio of reinforcement area, correction factor for moment of inertia of cracked sections is read from the Figure 3.4 [10] as 0.0245.

Then, the moment of inertia is calculated:

$$I = 0.0245(b)(d_c)^3 = 0.0245(1)(d_c)^3 m^4 \tag{3.13}$$

For a distributed load case, equivalent rigidity of a member with one end fixed and the according displacement are calculated as follows:

$$K_e = \frac{8E_cI}{H^4} = \frac{8(28)(10^9)(0.0245(d_c)^3)}{5^4} = 8.78(10)^6(d_c)^3(N/m^2)/m \tag{3.14}$$

$$X_e = \frac{r_u}{K_e} = \frac{230250(d_c)^2}{8.78(10^6)(d_c)^3} = \frac{2.62(10)^{-2}}{d_c} m \tag{3.15}$$

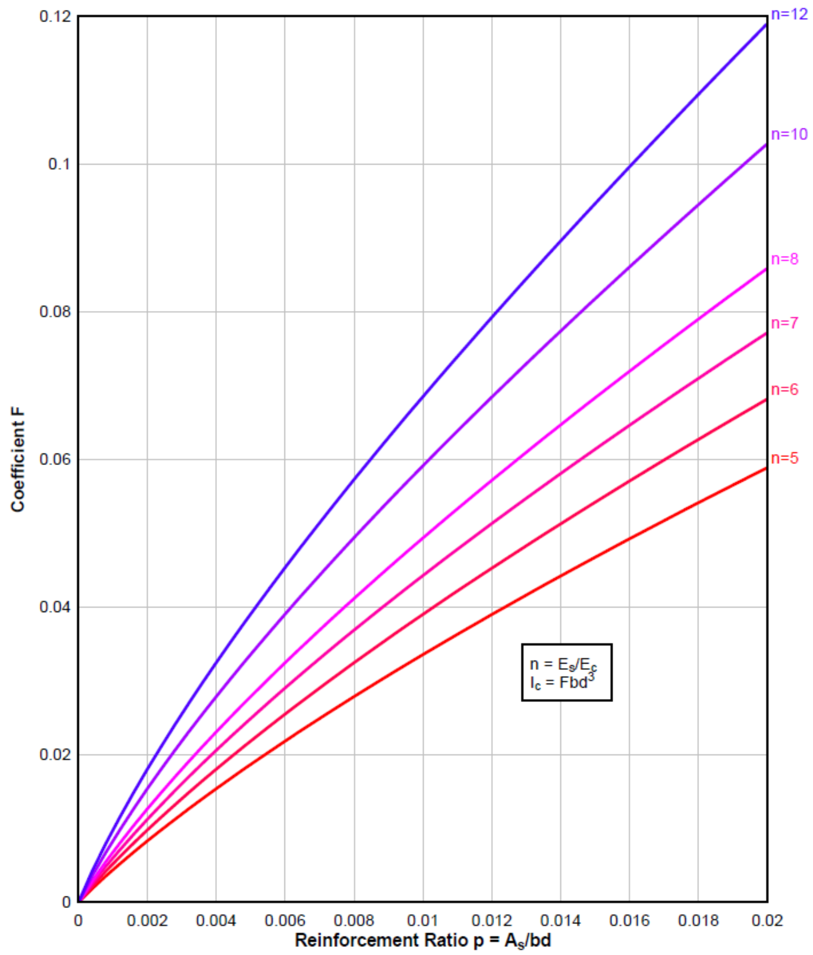


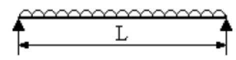
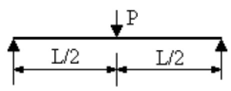
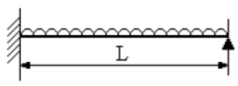
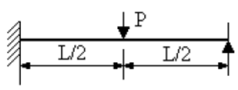
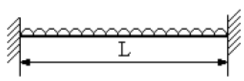
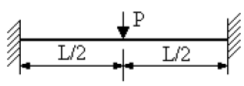
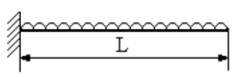
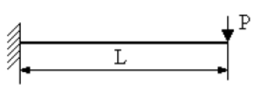
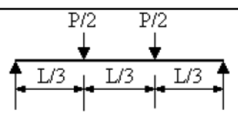
Figure 3.4. Coefficient for moment of inertia of cracked sections with equal reinforcement on opposite faces [10]

The equivalent load-mass factor, K_{LM} is read from the Table 3.1 as 0.66.

Then these values are used in the equation below to solve for d_c. This simplified equation is a customized version of UFC 340-2 specification [10].

$$\frac{i_r^2}{2K_{LM}m} = r_u(X_m - \frac{X_E}{2}) \tag{3.16}$$

Table 3.1. Load-Mass factors for different conditions. [10]

Edge Conditions and Loading Diagrams	Range of Behavior	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}
	Elastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.49	0.49
	Plastic	1.0	0.33	0.33
	Elastic	0.58	0.45	0.78
	Elasto-Plastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.43	0.43
	Elasto-Plastic	1.0	0.49	0.49
	Plastic	1.0	0.33	0.33
	Elastic	0.53	0.41	0.77
	Elasto-Plastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.37	0.37
	Plastic	1.0	0.33	0.33
	Elastic	0.40	0.26	0.65
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.24	0.24
	Plastic	1.0	0.33	0.33
	Elastic	0.87	0.52	0.60
	Plastic	1.0	0.56	0.56

Plugging the values, a third order equation is obtained for effective depth, d_c:

$$\frac{10095^2}{2(0.66)(2400d_c)} = 230250(d_c)^2(0.35 - \frac{2.62(10)^{-2}}{2d_c}) \tag{3.17}$$

From that equation d_c is solved as 0.749, so the effective depth, d_c is calculated as 0.75m

After the calculation of the effective depth, the area of longitudinal reinforcements is calculated.

$$A_s = \rho_s(b)(d_c) = 0.005(1000)(750) = 3750mm^2 \tag{3.18}$$

The required reinforcement diameter to meet the calculated needed area , A_s, with spacing, s=0.15m is calculated as ϕ=28mm.

Therefore, with clear covers included total thickness, t, is calculated as:

$$t = 40mm + (28mm/2) + 750mm + (28mm/2) + 40mm \cong 860mm \tag{3.19}$$

Thus, t is chosen as 0.9m.

The ratio of wall height to wall thickness results in a slenderness of 5.55 which is a reasonable value.

Final unit resistance, r_u, is calculated as:

$$r_u = 230250(d_c)^2 = 230250(0.75)^2 = 129515N/m^2 \tag{3.20}$$

Using again UFC-340-2 specification [10], the time needed to reach the maximum displacement is approximated as follows:

$$t_m \cong \frac{i_r}{r_u} = \frac{10095}{129515} = 0.0779s = 78ms \tag{3.21}$$

It is stated in UFC 340-2 that, when the ratio of t_m/T_s is grater than 3, design for impact becomes effective [10]. The ratio is calculated below:

$$\frac{t_m}{T_s} = 78/1.11 = 70.9 \tag{3.22}$$

Since the ratio, 70.9 is much larger than the limit value 3, the behaviour is not quasi-static. This check justifies previously done calculations about impulse loading.

3.2. Design for Shear

When bending limit is achieved, the ultimate shear stress is calculated as follows using UFC-340-2 Specification [10]:

$$v_u = \frac{r_u(H - d_c}{d_c} = \frac{129515(5 - 0.75)}{0.75} = 733918 = 0.734MPa \tag{3.23}$$

Also, for given effective depth, d_c and calculated reinforcements, capacity of cross-section is calculated using the formula provided by BS8110 specification [20]

$$v_c = 0.79(\frac{100A_s}{bd_c})^{\frac{1}{3}}(\frac{400}{d_c})^{\frac{1}{4}}(\frac{f_{dc}}{25})^{\frac{1}{3}}/1.25 = 0.477MPa \tag{3.24}$$

Since $v_c < v_u$, shear reinforcement is needed. The ultimate shear is in between $0.5v_c and v_c + 0.4$, so using the table provided by BS8110 Table 3.2, shear reinforcement can be calculated as follows [20]:

$$A_{gv} \geq 0.4b_v s_v/0.87f_{yv} \tag{3.25}$$

Table 3.2. Form and area of reinforcement in beams [20]

Value of v N/mm²	Form of shear reinforcement to be provided	Area of shear reinforcement to be provided
Less than $0.5v_c$ throughout the beam	See NOTE 1	—
$0.5v_c < v < (v_c + 0.4)$	Minimum links for whole length of beam	$A_{sv} \geq 0.4b_v s_v/0.95f_{yv}$ (see NOTE 2)
$(v_c + 0.4) < v < 0.8\sqrt{f_{cu}}$ or 5 N/mm²	Links or links combined with bent-up bars. Not more than 50 % of the shear resistance provided by the steel may be in the form of bent-up bars (see NOTE 3)	Where links only provided: $A_{sv} \geq b_v s_v(v - v_c)/0.95f_{yv}$ Where links and bent-up bars provided: see **3.4.5.6**
NOTE 1 While minimum links should be provided in all beams of structural importance, it will be satisfactory to omit them in members of minor structural importance such as lintels or where the maximum design shear stress is less than half v_c.		
NOTE 2 Minimum links provide a design shear resistance of 0.4 N/mm².		
NOTE 3 See **3.4.5.5** for guidance on spacing of links and bent-up bars.		

which gives us,

$$\frac{A_{gv}}{s_v} \geq \frac{0.4(1000)}{0.87(225)} = 2.04 \tag{3.26}$$

Besides, it is stated that s_v should not exceed 12 times the longitudinal reinforcement diameter $12 * 28 = 336$. Thus, if 300mm spacing is chosen, A_{gv} needed becomes $612mm^2$. Therefore, the needed link diameter is calculated as bigger than 8.05mm (assuming links are provided for every 4 bars), so the link diameter can be chosen as 10mm.

4. VALIDATION OF THE NUMERICAL TOOL

Before moving on with the analyses using numerical tool Air3D, a validation for the outputs of the tool needs to be assessed. This chapter contains two different checks for the validation: comparing the results of an experiment with the outputs of the Air3D computation with the same setup and also comparing the calculated peak pressures and impulses again, using Air3D tool with the values read from the diagrams of Baker [1], which are presented in Chapter 3.

4.1. Experiment Comparison

To verify the results of Air3D computations, an analysis of small-scale experiment [11] was made and the results of both analysis and the experiment were compared. This experiment was selected because it also takes into account a blast wall and measures the reflected pressure on the building behind the wall. Furthermore, another reason to select this experiment was that the blast wall used in the experiment is chosen to be long enough that a two-dimensional analysis represents the behavior well enough. This point was also stated in the article [11]. The authors have also made calculations using Second-Order "Hydrodynamic Advanced Research Code" hydrocode both in two dimensions and three dimensions and see the results are similar as it is seen in Figure 4.1.

The mentioned experiment was a small-scale version of a bigger experiment conducted at the Energetic Materials Research Test Center in Socorro, New Mexico. Test setup can be seen in Figure 4.2. In the study, 10 tests were performed and charge weights differ between 0.37 grams and 0.55 grams of PETN. The height of burst in all cases was 1.34cm and the wall height is 5.4cm. The article [11] shares the results of the test in which a charge weight of 0.475g PETN was used. Also, the distance from charge to the wall was 10.04cm and the distance from the wall to the building was 6.69cm. The gauges 3, 4 and 5 were at positioned at heights of 4cm, 8cm and 12cm, respectively.

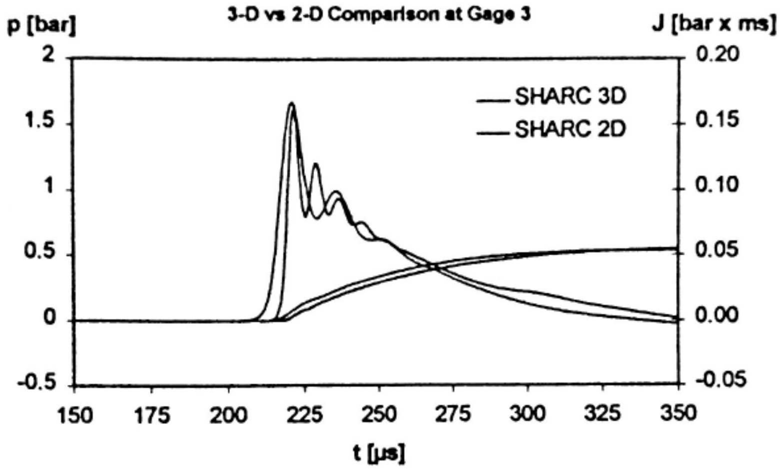


Figure 4.1. Comparison of 2D and 3D calculations.

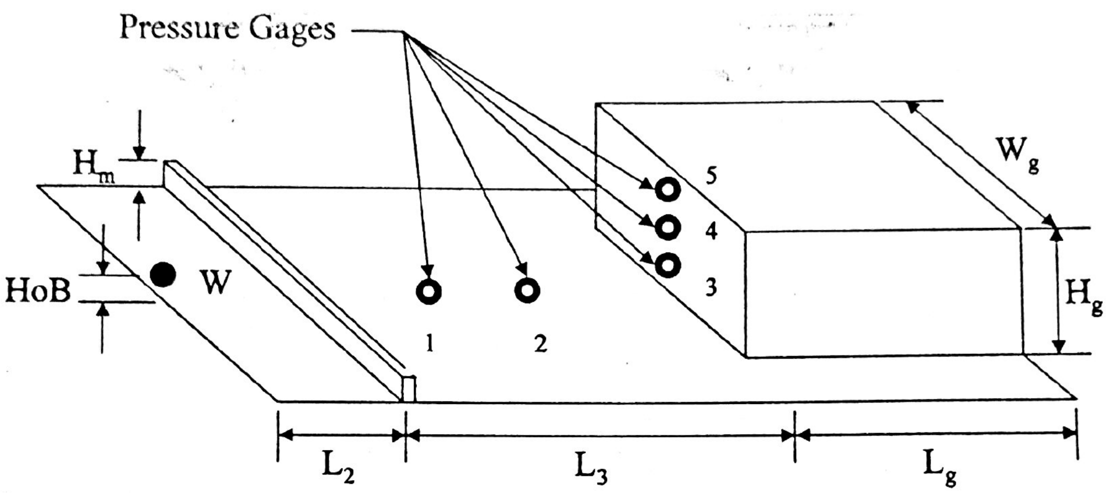


Figure 4.2. Experimental setup sketching.

The same test setup was created for Air3D analysis. The input of charge weight was in kg of TNT, and in the same article [11] it is stated that there is a 1.2 coefficient to convert PETN to TNT. Using this coefficient the equivalent TNT amount used in Air3D analysis was 0.57g. Also, three different cell sizes (0.5mm, 0.2mm and 0.1mm) were used in two-dimensional analysis and the results were compared. Results of 0.1mm and 0.2mm cell size analyses were very similar and considering the performance over time, 0.2mm cell size was chosen for two-dimensional analysis.

After conducting the analysis, the impulses and pressures presented and calculated were compared.

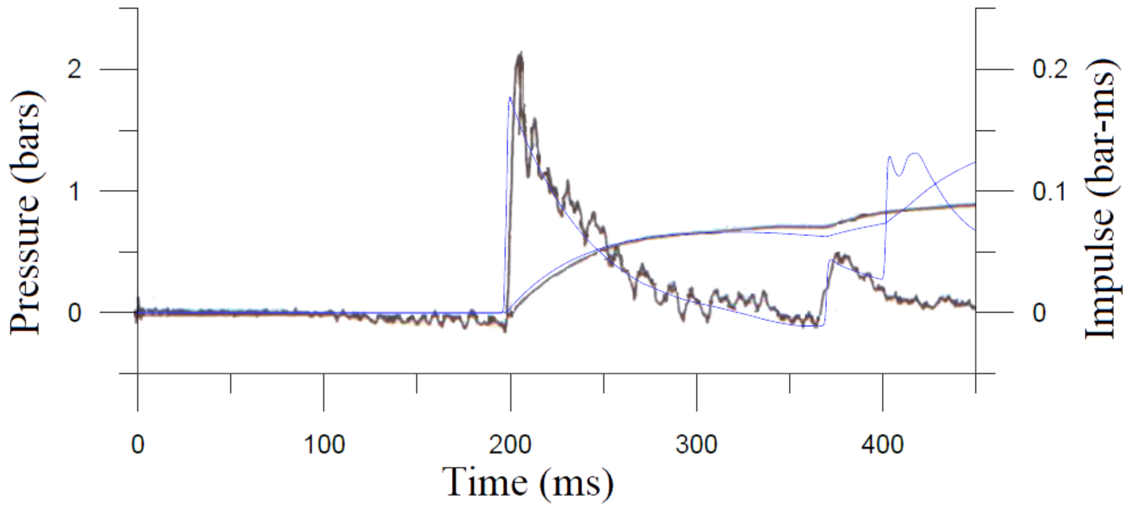


Figure 4.3. Comparison of Air3D calculation results (blue) and experiment results for gauge 3 (black).

As it is seen in Figures 4.3-4.5 the results were similar. The only difference was that the gauges in the experiment could not record the second positive pressure wave. This may be due to the fact that the wall in the experiment could be destroyed after the blast and there would be no reflections from the back of the wall. Thus, the Air3D computation was validated by the results of the experiment and the Air3D tool provides reliable results. Besides, the article [11] also presents a shadow-graph from another test in which the charge is 0.375g of PETN. To have a more visual comparison,

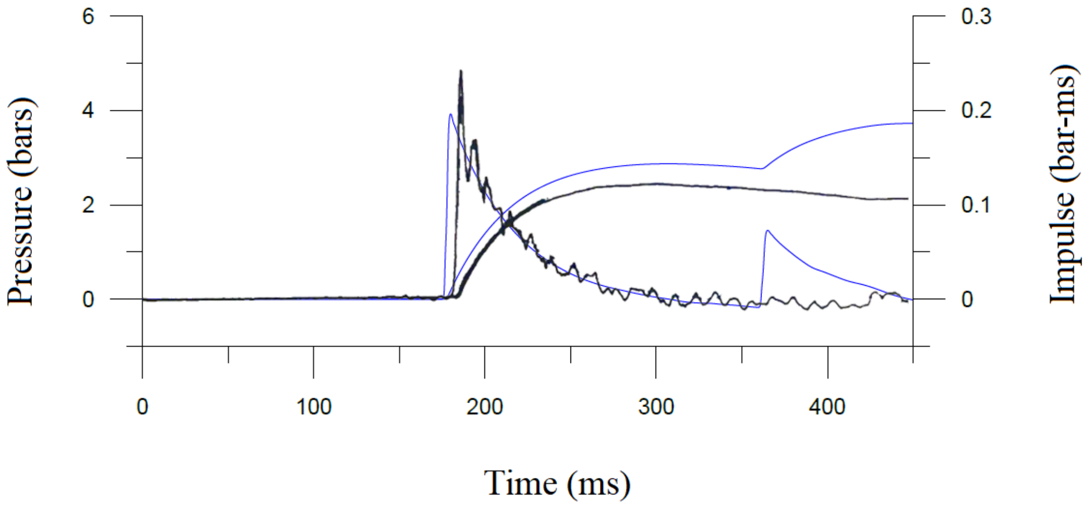


Figure 4.4. Comparison of Air3D calculation results (blue) and experiment results for gauge 4 (black).

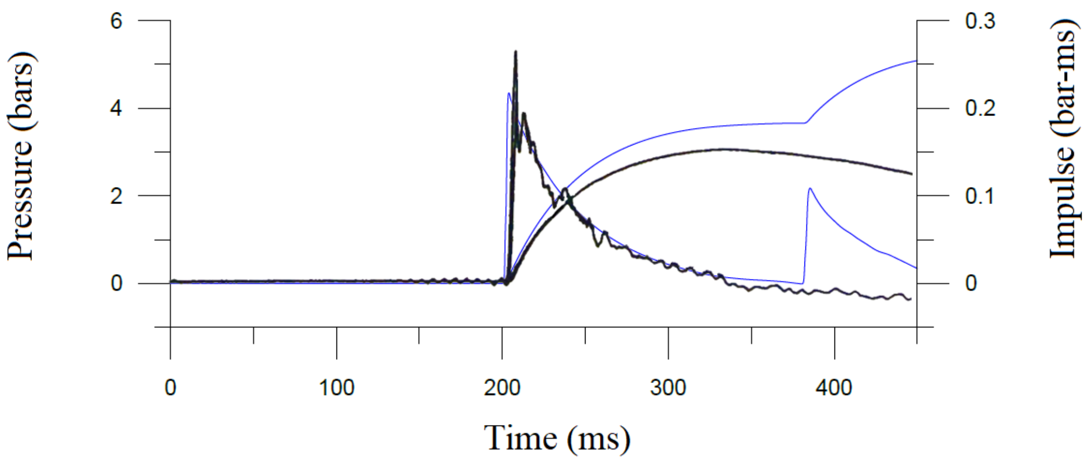


Figure 4.5. Comparison of Air3D calculation results (blue) and experiment results for gauge 5 (black).

this analysis was also made using Air3D and the bitmap representing the pressures with the shadow-graph can be seen in Figure 4.6.

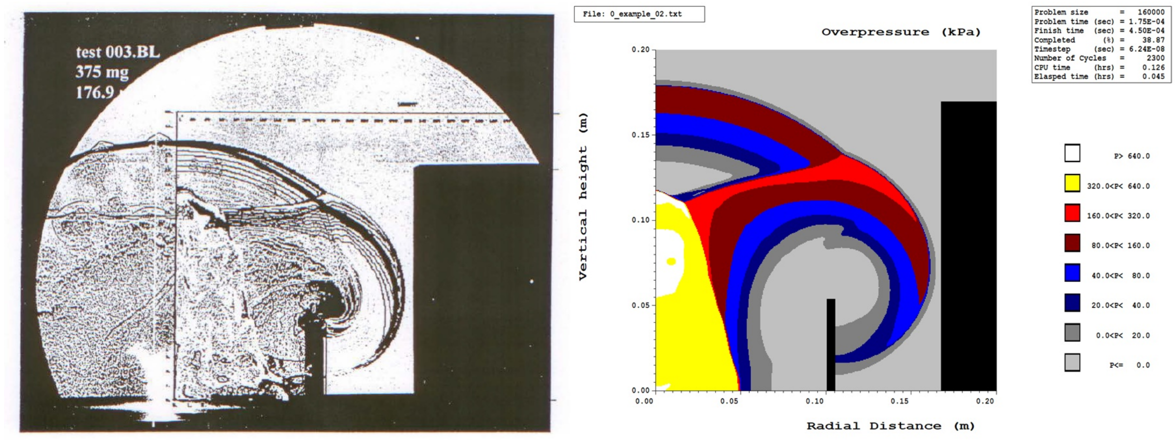


Figure 4.6. Shadow-graph presented in article [11] (left) and corresponding Air3D bitmap (right).

4.2. Design Chart Comparison

As stated in Chapter 3, the design charts provided by Baker [1] is actively used in design for blast loads. Therefore, the Air3D results should show similar results for similar conditions.

In the study, the wall-blast distance was chosen as 2m and TNT weight is 150kg. Therefore, as calculated in Chapter 3, a scaled distance of $0.3764m/kg^{1/3}$ was obtained. Also, it was stated that for this scaled distance, the design charts show an impulse of 10095Pa.s. Furthermore, if Figure 3.2 is examined for the same scaled distance, a reflected peak pressure, P_r of approximately 50MPa is read from the diagram. To have further validation, these values were also checked with the outputs of the Air3D tool.

An analysis to calculate the pressures on the blast wall was also made. These pressures can be seen in Figure 4.7. The peak reflected pressure was around 45000kPa in this chart. Calculated impulse caused by first positive pressure wave was around 10700 Pa.s.

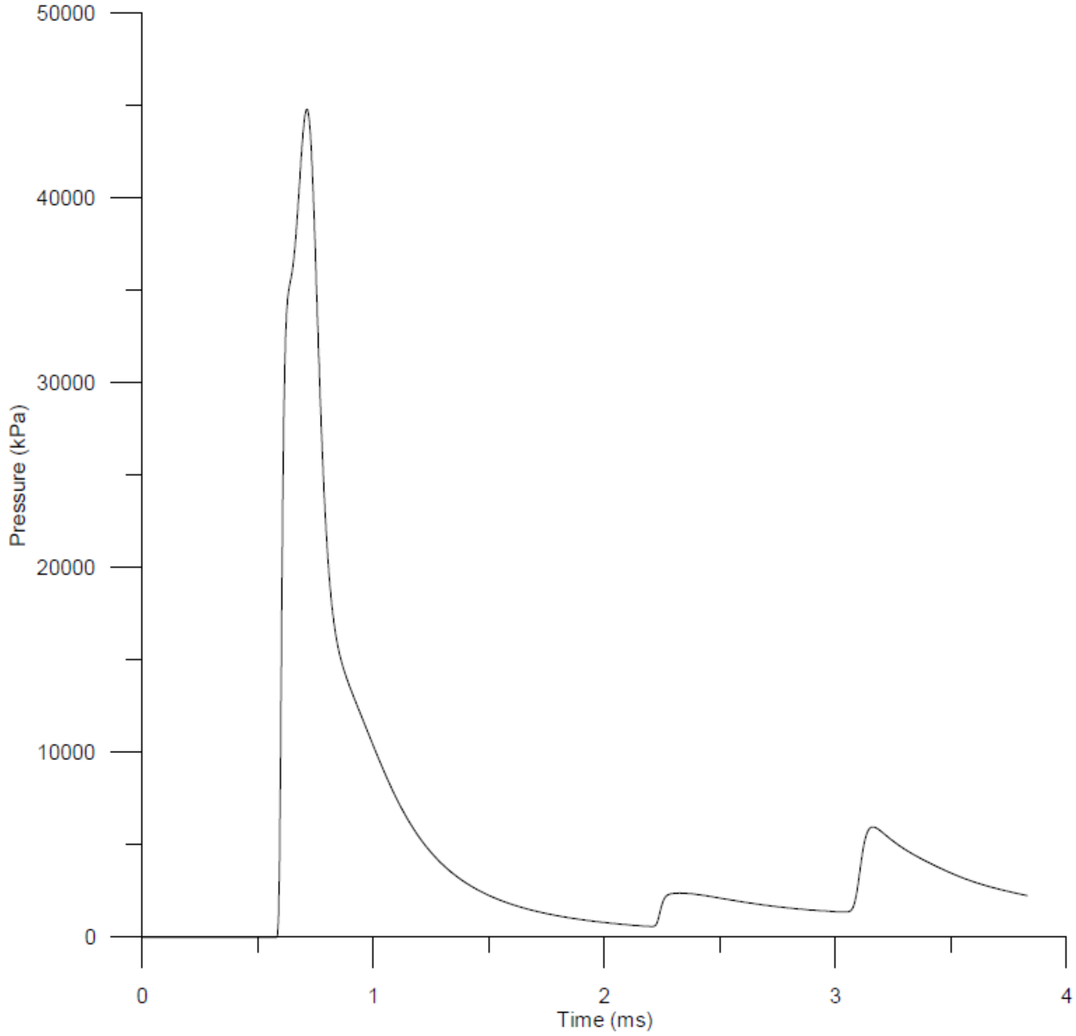


Figure 4.7. Calculated pressures on blast wall.

These peak pressure and corresponding impulse values were close enough to the values in the design chart. Also, previous work with different cell sizes also can lead to the assumption that as the cell sizes decrease the peak pressure increases. However, that pressure is achieved only in a small fraction of time so it does not change the impulse excessively. Hence, closer peak pressures to the pressures read from design charts can be computed with smaller cell sizes.

5. METHODOLOGY

In this study, the effects of having different blast walls and different stand-off distances on the blast loading to a building in case of an attack scenario were examined. There are a number of variables affecting the blast load on buildings. TNT amount is the most obvious one.

In order to choose a TNT amount to use in the analyses, a blast scenario was chosen to present more tangible results. The loading scenario was a car bomb. When FEMA guidelines [12] were examined, it was understood that an automobile can carry 45 to 200kg of TNT. In this study, the TNT amount was chosen as 150kg. There was a car bomb incident in Bogotá, Colombia [21]. In that incident, a car with 200kg of ANFO (Ammonium nitrate and chlorate + fuel oil) was exploded inside a building, which led to 38 fatalities, many injuries and serious structural damage. When TNT equivalent was calculated, around 150kg of TNT created the same effect using an equivalent factor of 0.73 [22].

The distance from the blast to the wall was taken as 2 meters, considering a sidewalk and a building height of 24m, which is based on a regular office building plan. Also, the wall thickness was chosen as 0.9m as calculated and discussed in Section 3.

The above-mentioned variables were kept constant throughout this study. The changes were made in wall height and also the distance between the blast wall and the building. The wall heights used in the analyses were 2m, 3m, 4m, and 5m. Also, no blast wall cases were analyzed. The wall-building distances used were 5m, 10m, 15m, and 20m. Combining these cases, 20 analyses were conducted is made. Table 5.1 represents the summary of these analyses.

One last variable to decide was the cell size for two-dimensional analysis. The optimum cell size had to be chosen in order to avoid unnecessary computational efforts and get the results as accurate as possible. In order to achieve that, three different

Table 5.1. Summary of analyses.

Analysis #	**Wall Height**	**Wall-Building Distance**
1	No Wall	5m
2	No Wall	10m
3	No Wall	15m
4	No Wall	20m
5	2m	5m
6	2m	10m
7	2m	15m
8	2m	20m
9	3m	5m
10	3m	10m
11	3m	15m
12	3m	20m
13	4m	5m
14	4m	10m
15	4m	15m
16	4m	20m
17	5m	5m
18	5m	10m
19	5m	15m
20	5m	20m

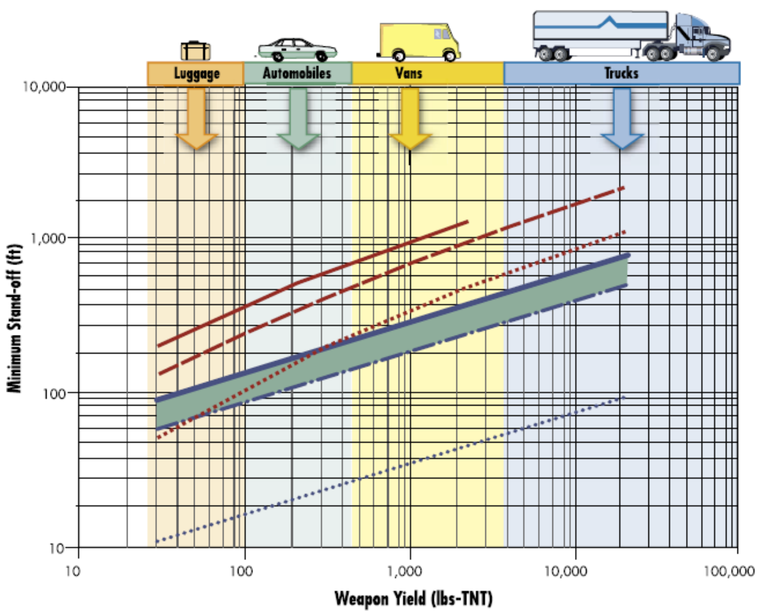


Figure 5.1. Classifications made by FEMA on vehicle types and TNT weights. [12]

analyses are made using 0.05m, 0.10m, and 0.15m cell sizes. The results of each for an arbitrary point (point 4, at 4m height) on the building is shown in Figure 5.2 and Figure 5.3.

Figure 5.2 represents the pressure over time and Figure 5.3 represents impulse over time. As it is seen, the pressure calculations differ at some points, however, the impulse was a more important input for the design against blast. Again, when Figure 5.3 is examined it can be seen that the impulses are quite similar. Thus, considering the results and also the required time to make the analyses, 0.1m cell size was chosen for this study.

During each analysis, appropriate setup was formed as an input for Air3D tool and pressures in each meter of the building (24 points in total) were recorded. Some outputs of the simulations can be seen in Figure 5.4 and Figure 5.5. Especially in Figure 5.5, the repeated reflections from wall and building can be observed.

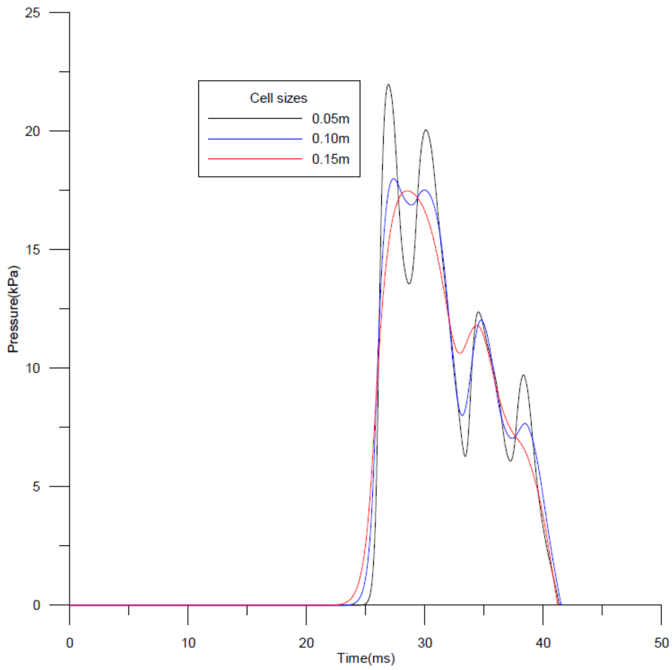


Figure 5.2. Recorded pressures on three analyses with different cell sizes.

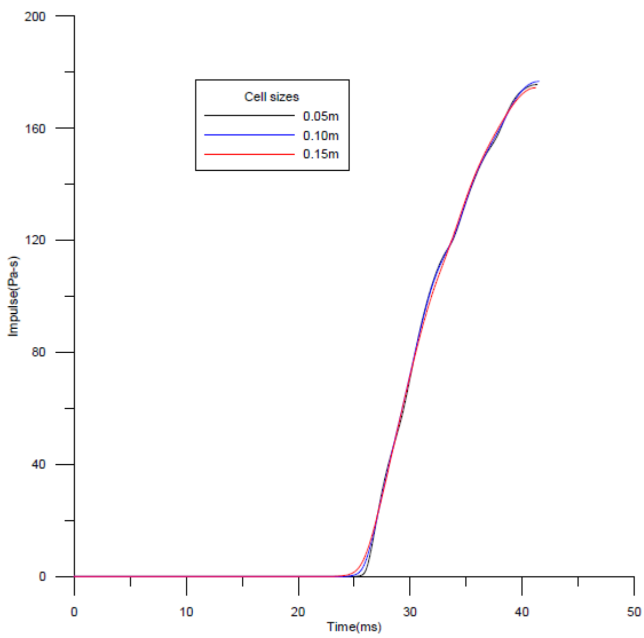


Figure 5.3. Calculated impulses after three analyses with different cell sizes.

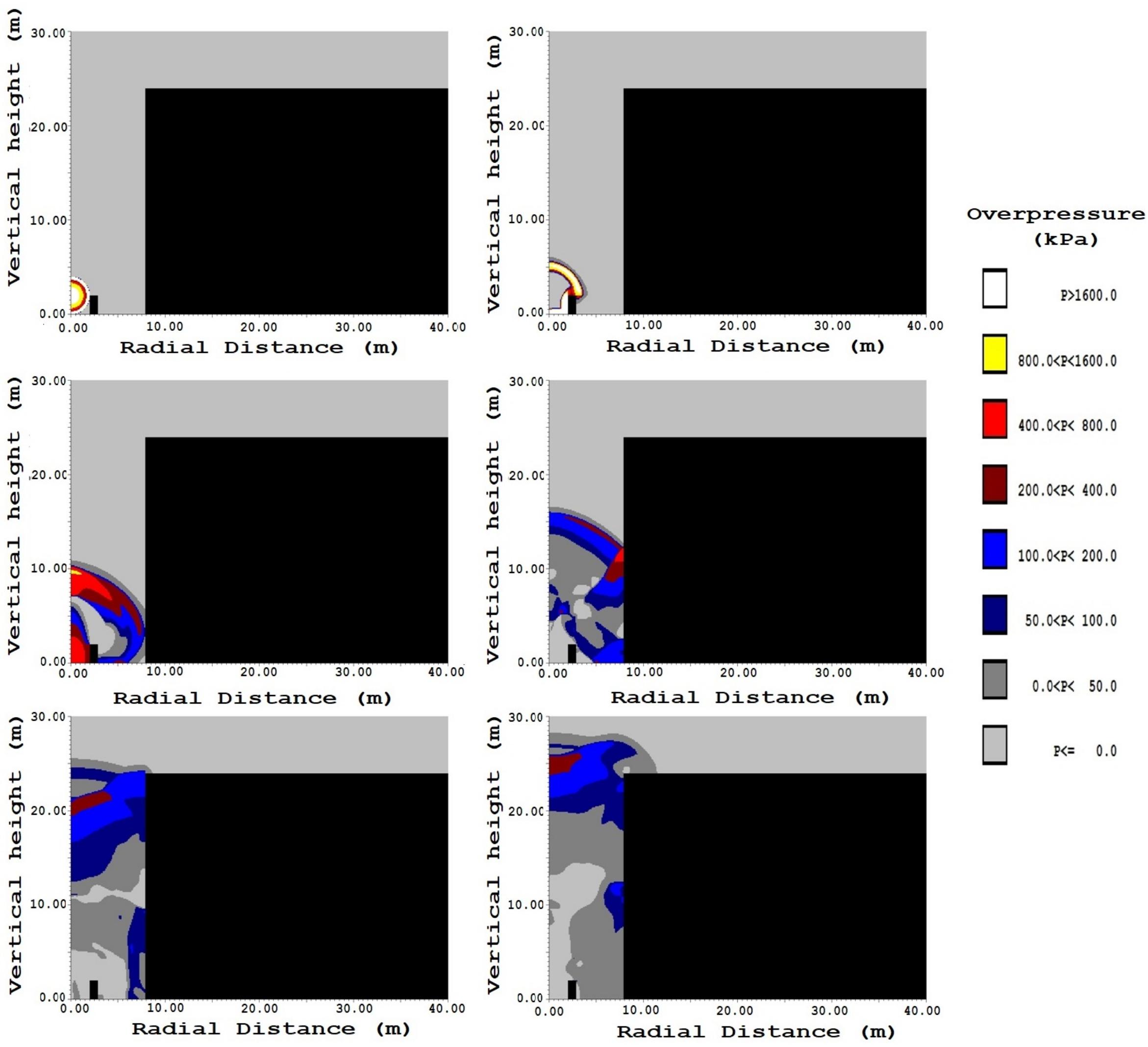


Figure 5.4. Bitmaps from Analysis 5 (with 2m wall and 5m wall-building distance).

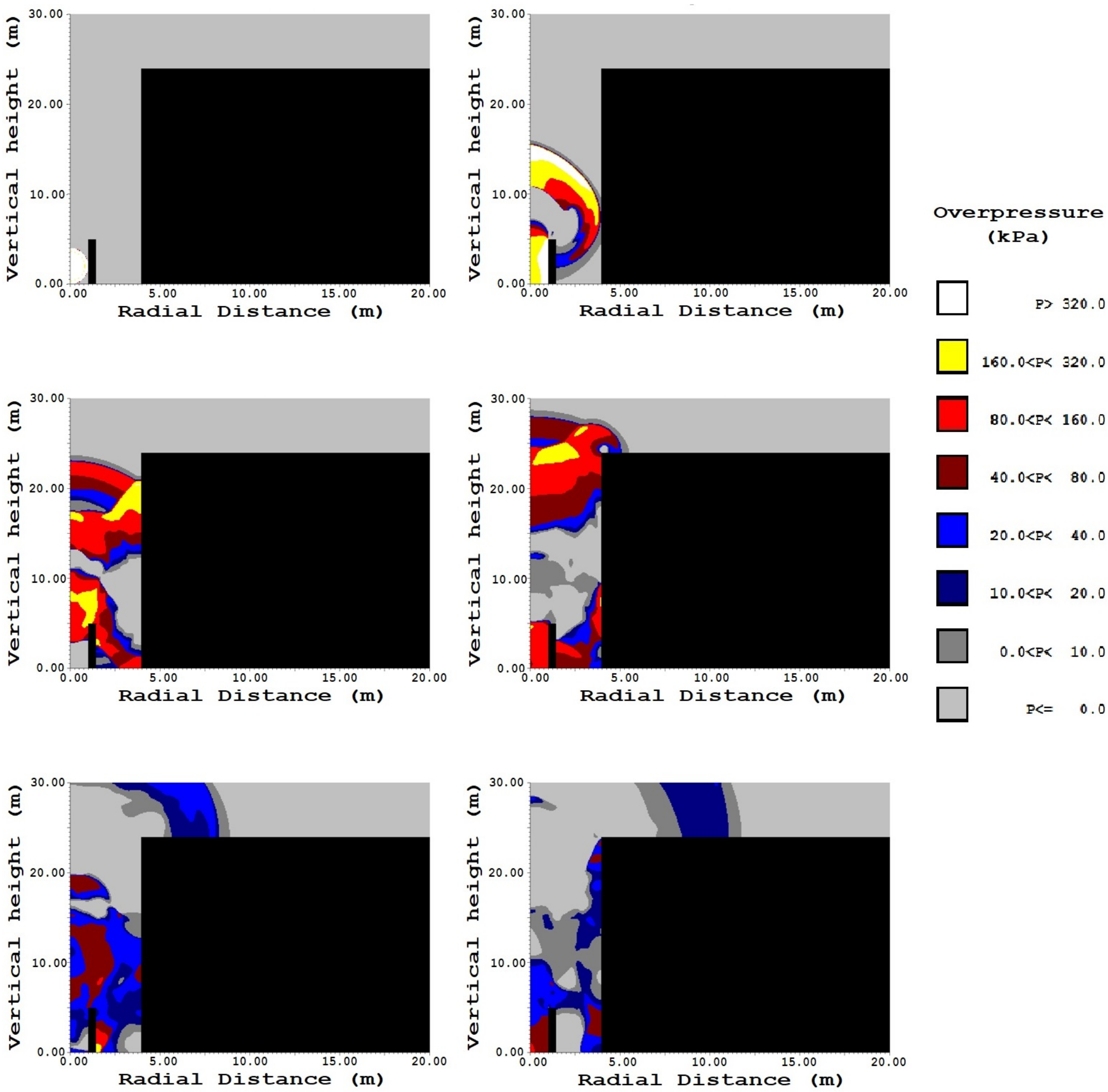


Figure 5.5. Bitmaps from Analysis 17 (with 5m wall and 5m wall-building distance).

After the analyses were done, the impulse loading was calculated for each analysis. Then, the effects of different blast walls and distances were examined for each point on the front face of the building.

6. RESULTS AND DISCUSSION

In this chapter, the results of the analyses are presented and they are discussed in detail. As it is stated in Chapter 5, analyses of 20 different combinations were made and pressures were recorded with 1m intervals on the façade of the building. These pressure values can be found in Appendix A.

It is discussed in the previous chapters that, the impulse is a better input than peak pressure for design purposes. Hence, the impulses were calculated by integration of pressure with respect to time. Then the maximum impulse values were recorded for each point. Using these records, trends have been observed and discussed.

6.1. Wall Height Parameter

In order to see the wall height effect, analyses with the same wall-building distances are grouped into the same graphs and presented in this section. Graphs of height vs impulse are presented, where height represents the height of the point on building façade and impulse is the maximum impulse that the point experiences during its analysis.

6.1.1. Analyses With Wall-Height Distance of 5m

In Figure 6.1 the impulses from analyses with a wall-building distance of 5m are presented (Analyses 1-5-9-13-17 in Table 5.1).

The positive effect of the blast walls was clearly seen in low heights of the building. As the height increased, the protection effect faded. It can be seen that the walls provide protection at the façade for even higher points than their own height.

The reductions in the impulse due to the blast perimeter walls can be seen in Figure 6.2. These reductions were calculated by dividing the difference between the

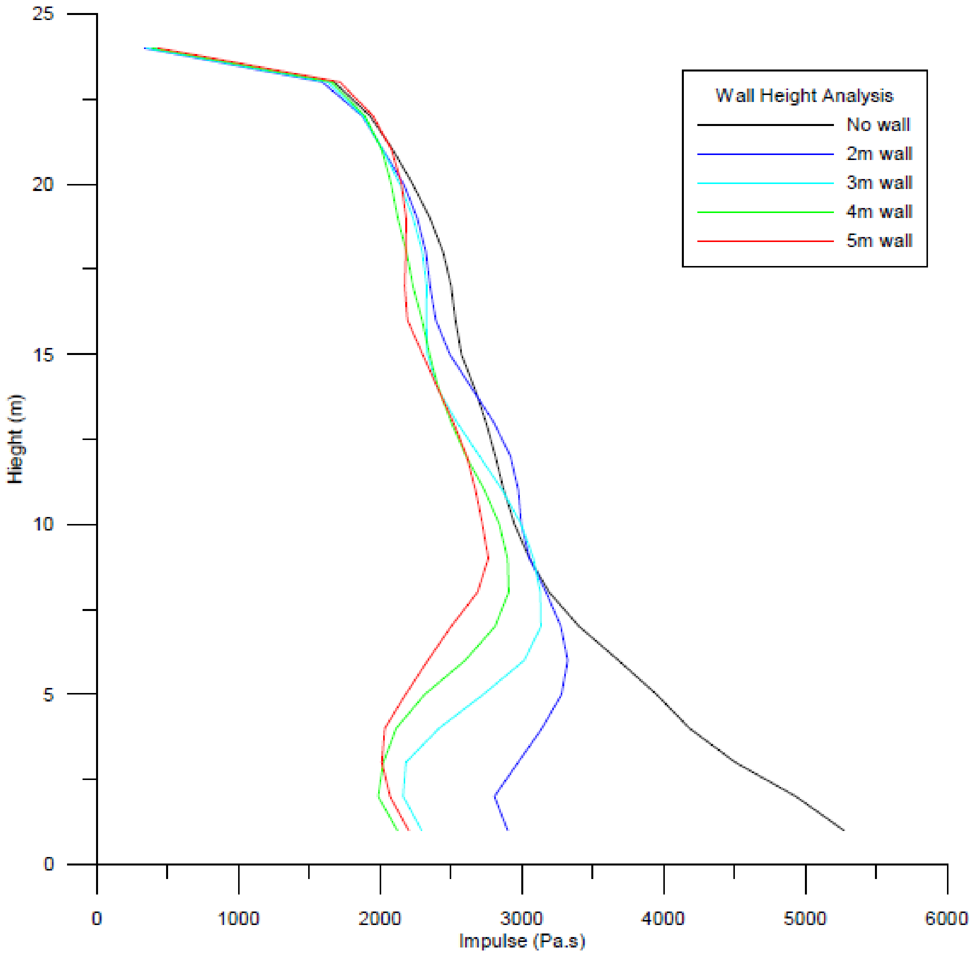


Figure 6.1. Impulses on building (5m wall-building distance).

cases with wall and without wall by the impulses of no wall cases. As it is seen in Figure 6.2, roughly 50% protection within wall heights was provided by the walls in this distance. For this distance, the protection level was high at lower elevations and it fades quickly around 10 meters. Then, more protection was provided especially for 3, 4 and 5m wall cases. It can be said that the 2m wall was a bit inadequate in protection terms from the others at this distance. Generally, the reduction percentage increases with an increase in wall height.

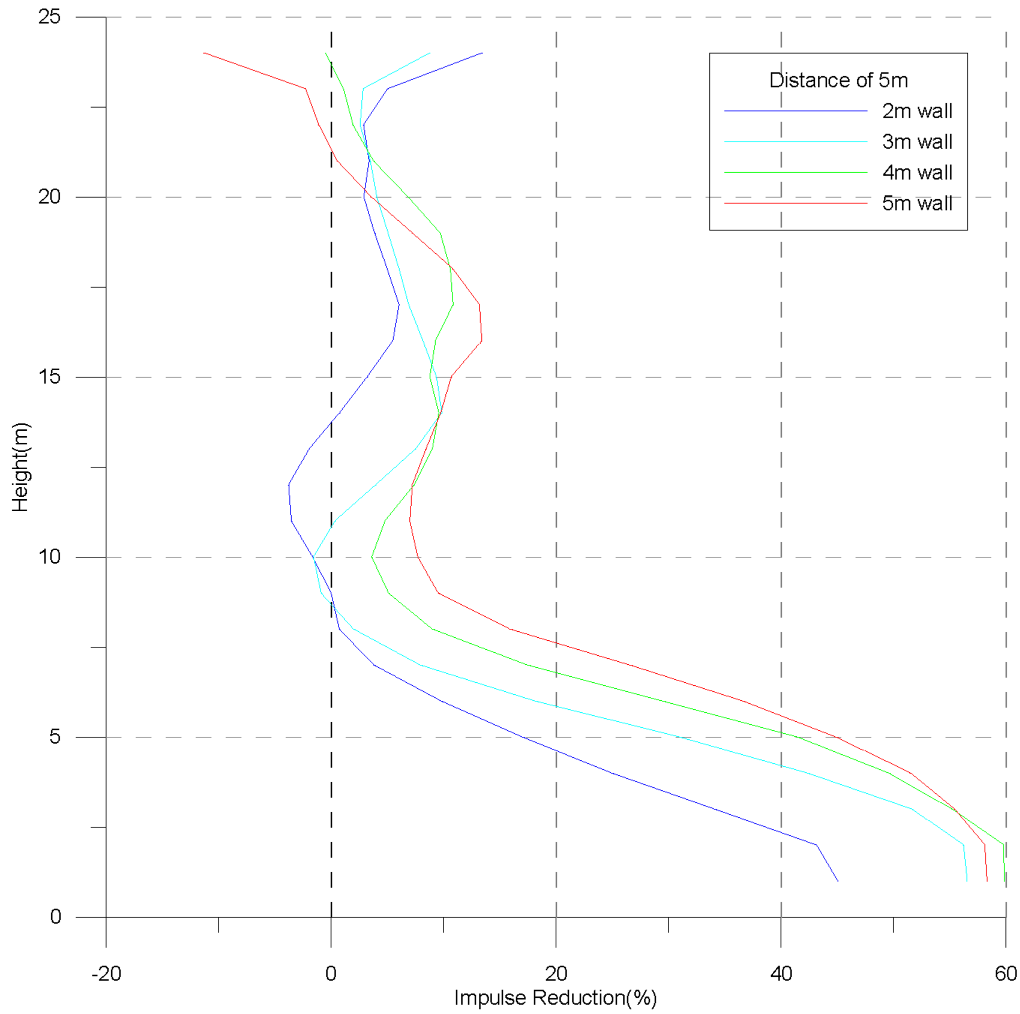


Figure 6.2. Reduction percentages in impulses (5m wall-building distance).

6.1.2. Analyses With Wall-Height Distance of 10m

In Figure 6.3 the impulses from analyses with a wall-building distance of 10m are presented (Analyses 2-6-10-14-18 in Table 5.1).

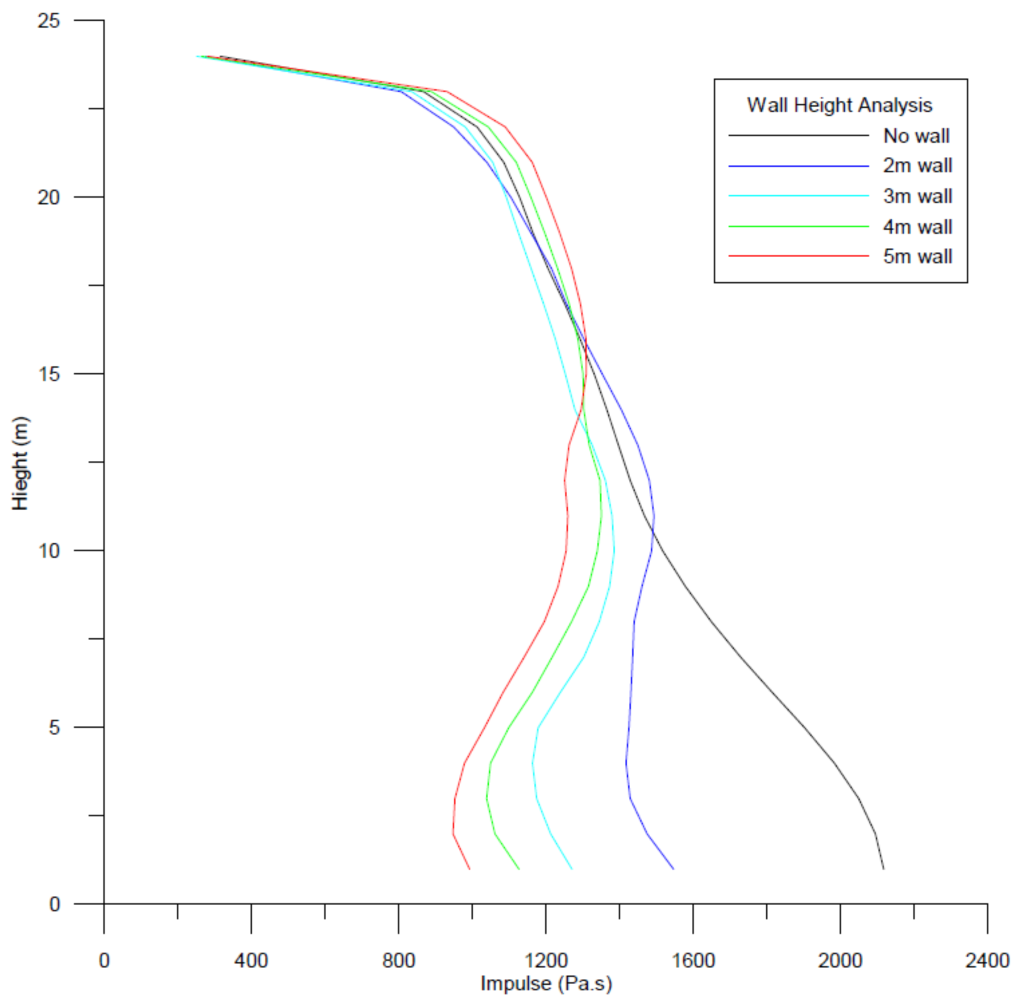


Figure 6.3. Impulses on building (10m wall-building distance).

Again, the positive effect of the blast walls was clearly seen in low heights of the building. Then as the height increased, the protection effect faded. However, it can be seen that the walls provided protection at the façade for even higher levels than the previous cases with 5m wall-building distance.

The reductions in the impulse due to the blast walls can be seen in Figure 6.4. Roughly 30-50% protection was provided by the walls within their heights at this distance. The reduction percentage, again, increased with the increase in wall height until around 13m height. From that point up, there was a reverse correlation between the protection and the wall height, meaning that the 5m wall even caused an increase in the impulse levels.

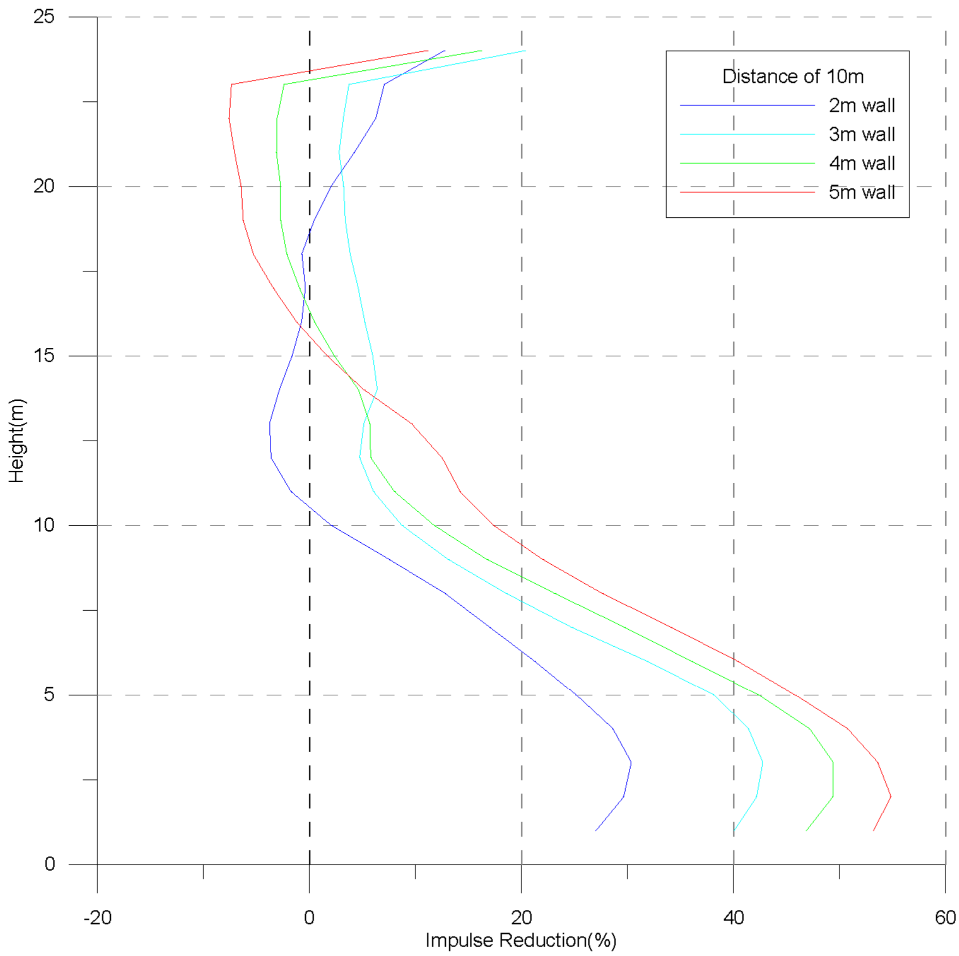


Figure 6.4. Reduction percentages in impulses (10m wall-building distance).

6.1.3. Analyses With Wall-Height Distance of 15m

In Figure 6.5 the impulses from analyses with a wall-building distance of 15m are presented (Analyses 3-7-11-15-19 in Table 5.1).

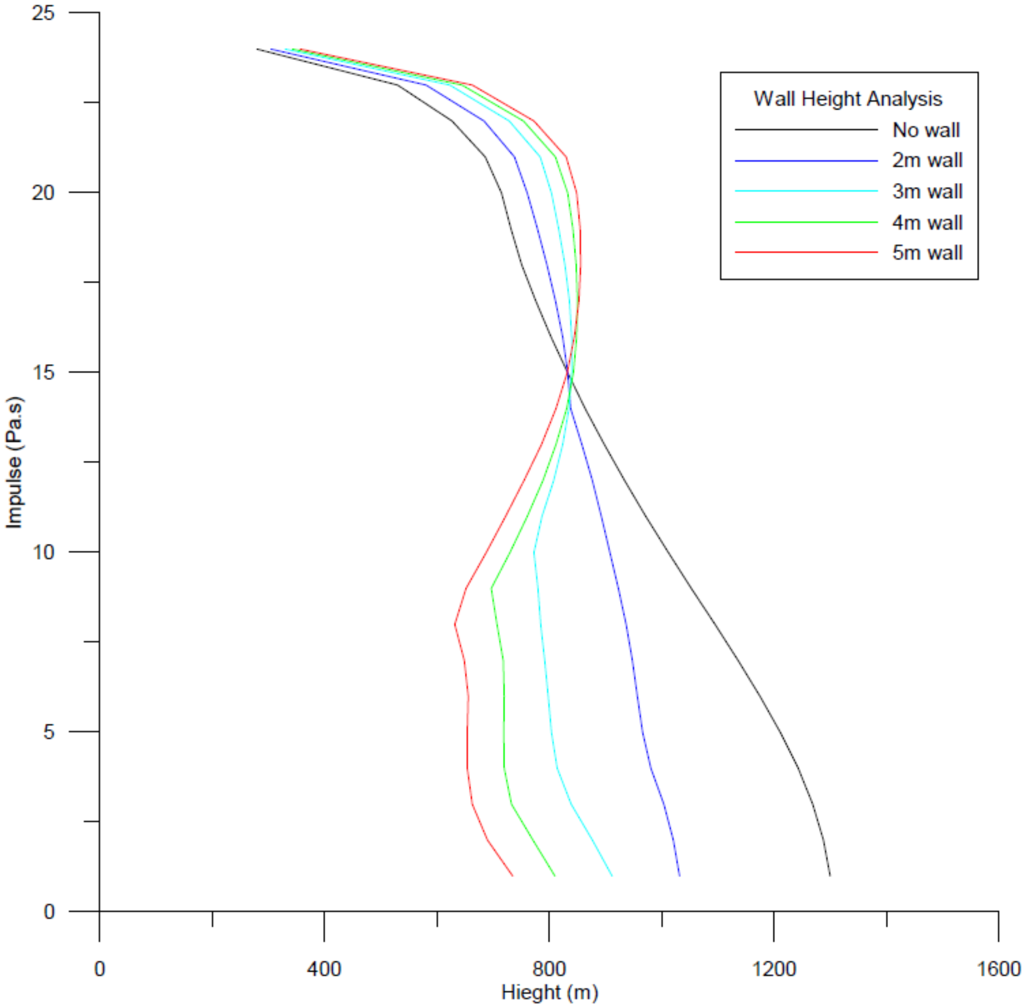


Figure 6.5. Impulses on building (15m wall-building distance).

The fading trend of protection towards higher elevations is again visible in these cases. However, it can be seen that the walls provided protection at the façade for even higher points than the previous cases.

The reductions in the impulse due to the blast walls can be seen in Figure 6.6. Roughly 20-45% protection was provided by the walls along their heights at this distance. The reduction percentage, again, increased with the increase in wall height until 15m. From this point up, the reverse correlation mentioned in the 10m distance case was seen more clearly. For the 5m wall case, the impulses were increased up to 25% at the highest points of the building.

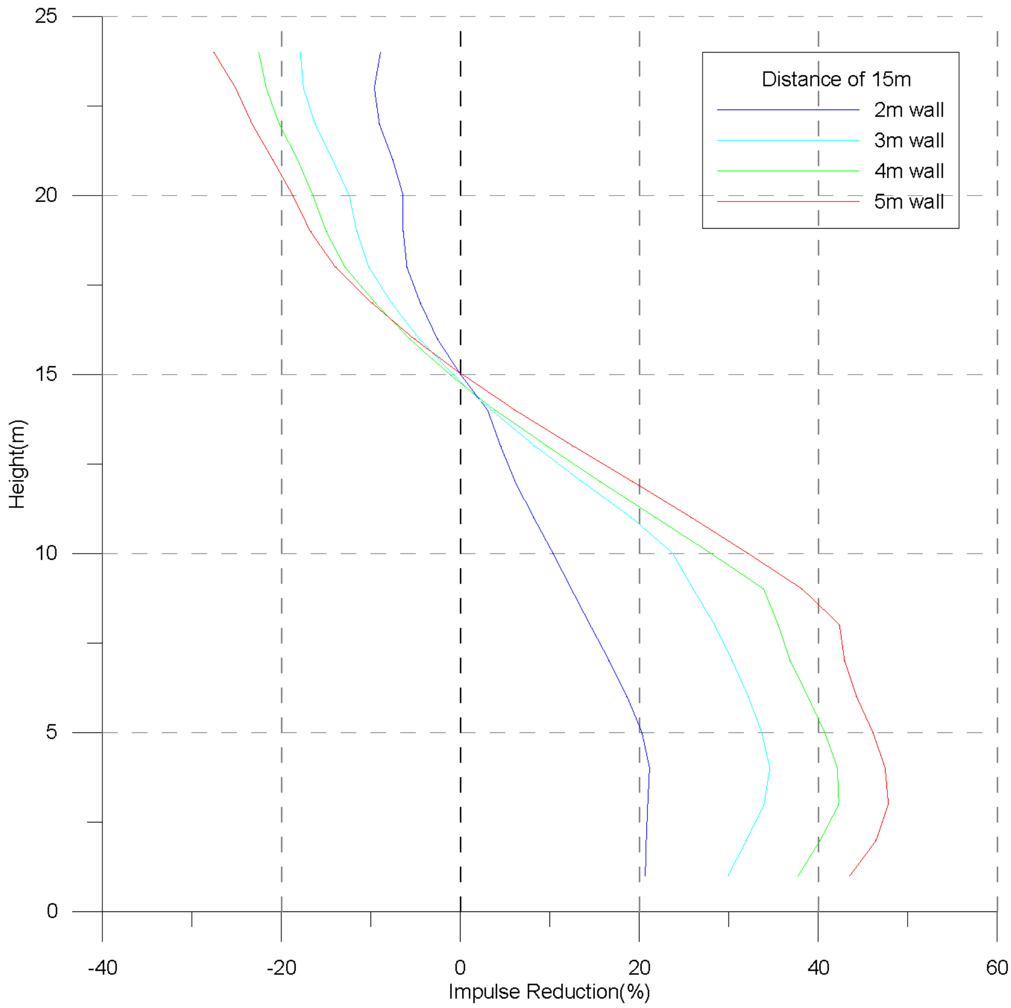


Figure 6.6. Reduction percentages in impulses (15m wall-building distance).

6.1.4. Analyses With Wall-Height Distance of 20m

In Figure 6.7 the impulses from analyses with a wall-building distance of 20m are presented (Analyses 4-8-12-16-20 in Table 5.1).

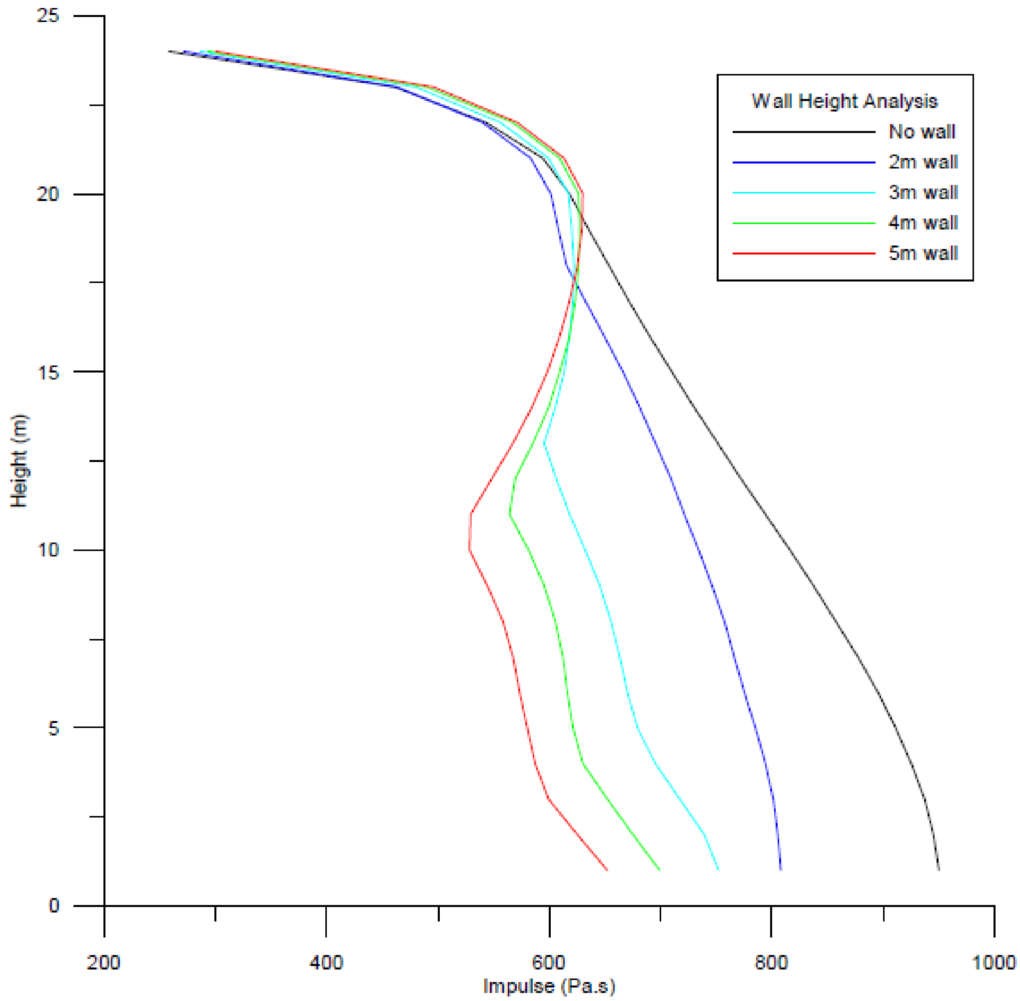


Figure 6.7. Impulses on building (20m wall-building distance).

Similar to other cases, the positive effect of the blast walls was clearly observed in low heights of the building. Although protection levels were decreased at higher elevations, the walls provided protection at the façade for even higher points than the previous cases.

The reductions in the impulse due to the blast walls can be seen in Figure 6.8. Roughly 15-35% protection was provided by the walls along their heights at this distance. The reduction percentage, again, increased with the increase in wall height up to 17m. Again from that point up, the mentioned reverse effect from the previous cases started.

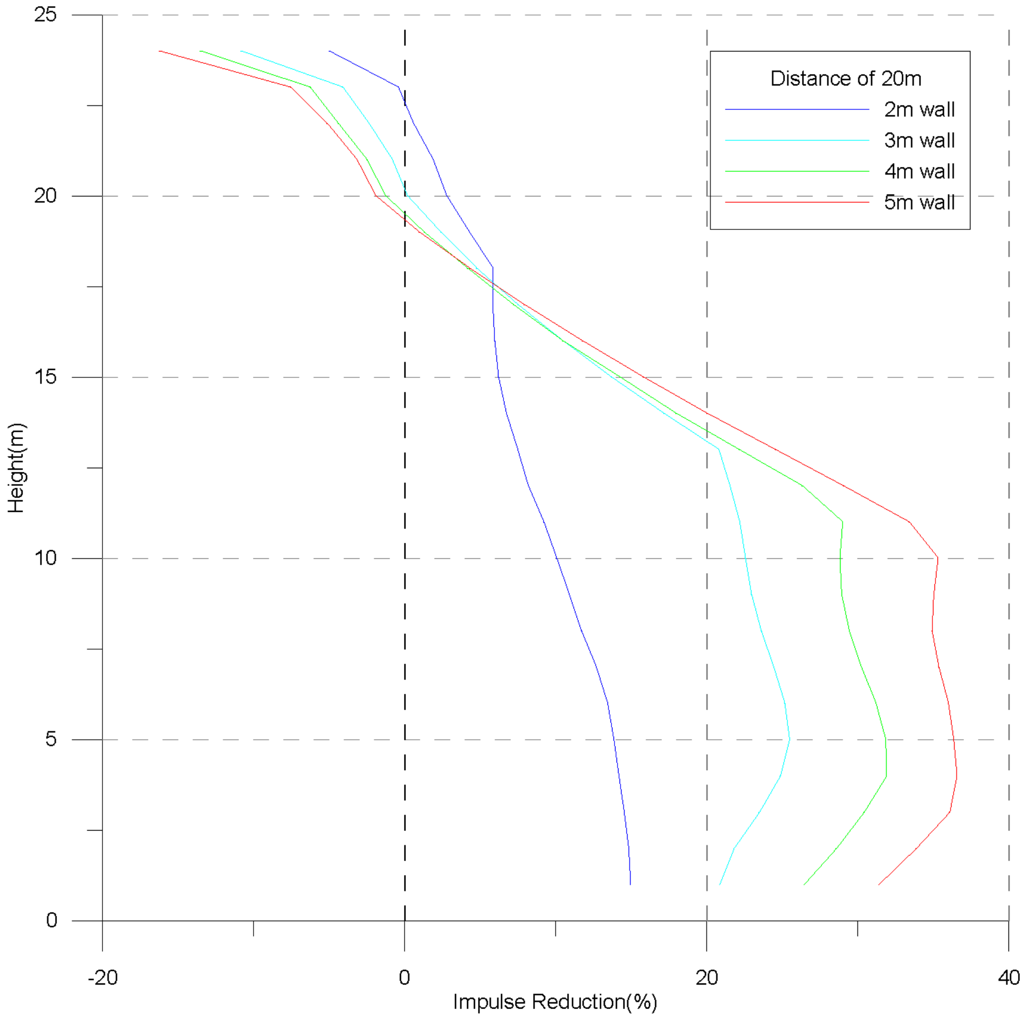


Figure 6.8. Reduction percentages in impulses (20m wall-building distance).

6.1.5. Summary

As a result, there was a positive correlation between the reductions and blast wall height. However, this effect was reversed after some heights depending on the distance between the wall and the building. This effect could be explained by stating that the walls changed the first impact point of the shock wave. In Figure 6.9 two different bitmaps are given for a distance of 15m. The first contact point of no wall case and the 5m wall case clearly shows that the blast wall made initial contact point of the wave at a higher elevation. Hence, the impulses were reduced in the lower elevations, and increased in the higher elevations, due to the redirected blast waves.

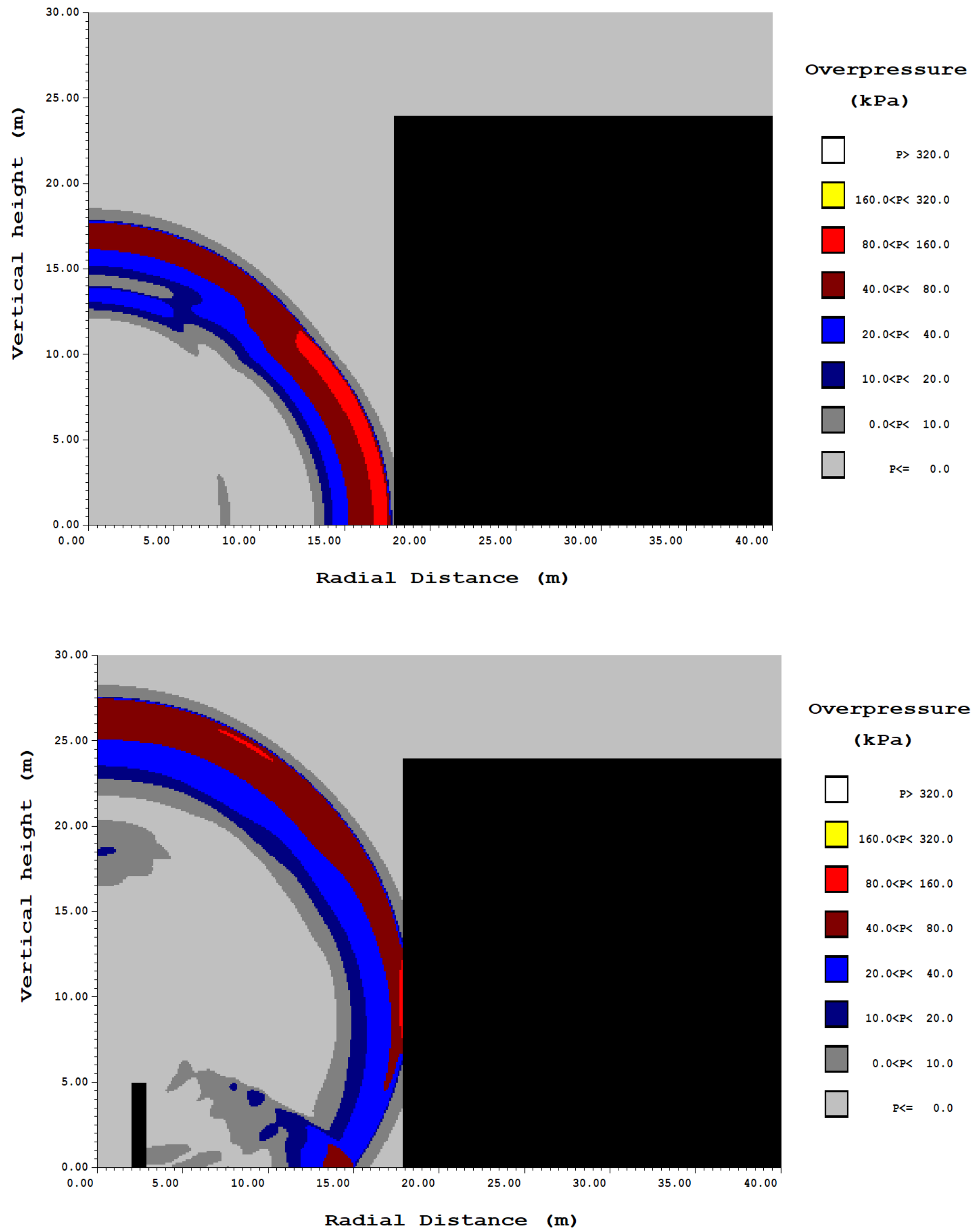


Figure 6.9. Bitmaps of Analysis 3(top) and Analysis 19(bottom).

6.2. Wall-Building Distance Parameter

In order to see the distance effect, analyses with the same walls were grouped into the same graphs and presented in this section. Graphs of height vs impulse were presented, where height represents the height of the point on building façade and impulse is the maximum impulse that the point experiences during the analysis.

In Figures 6.10-6.14 impulses from analyses with no walls (Analyses 1-4), 2m wall (Analyses 5-8), 3m wall (Analyses 9-12), 4m wall (Analyses 13-16) and 5m wall (Analyses 17-20) are presented, respectively. These analyses are summarized in Table 5.1.

The reduction in the impulses was clearly observed in each case. Adding the first 5m to the stand-off distance helped a lot in decreasing the blast load. However, adding each extra 5m helped less and less.

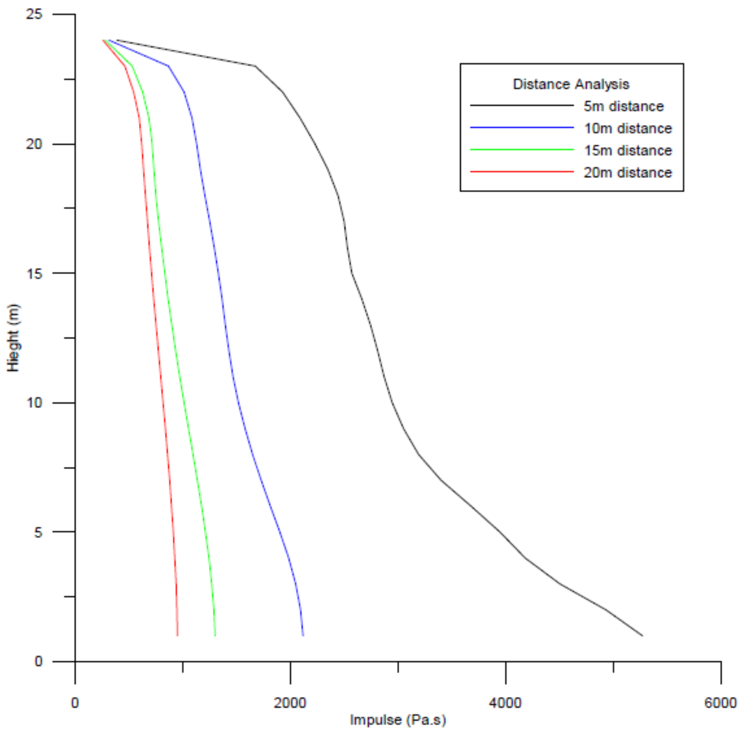


Figure 6.10. Impulses on building (No wall).

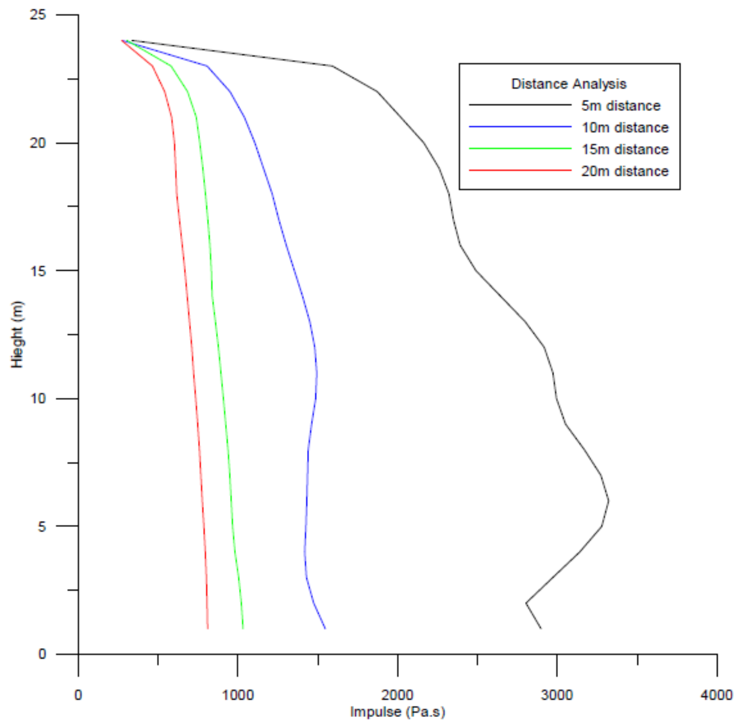


Figure 6.11. Impulses on building (2m wall).

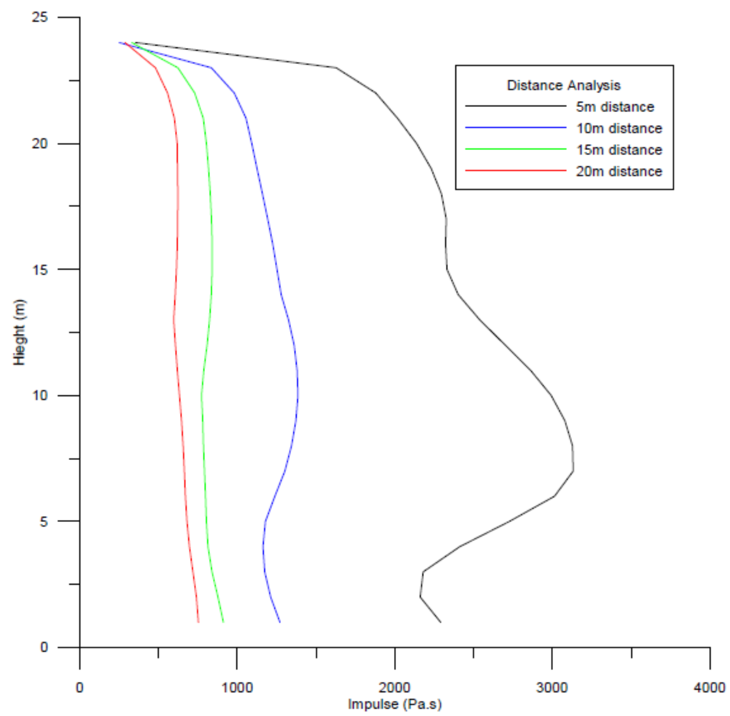


Figure 6.12. Impulses on building (3m wall).

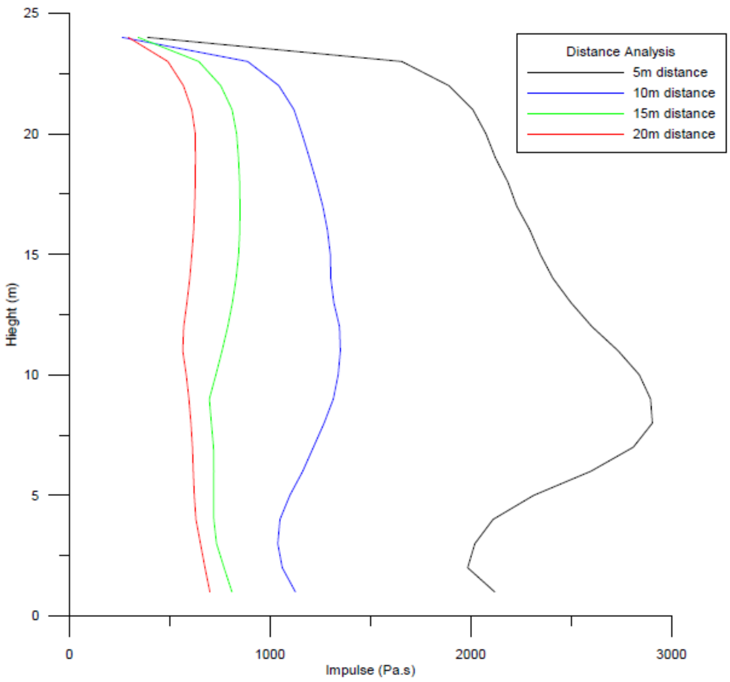


Figure 6.13. Impulses on building (4m wall).

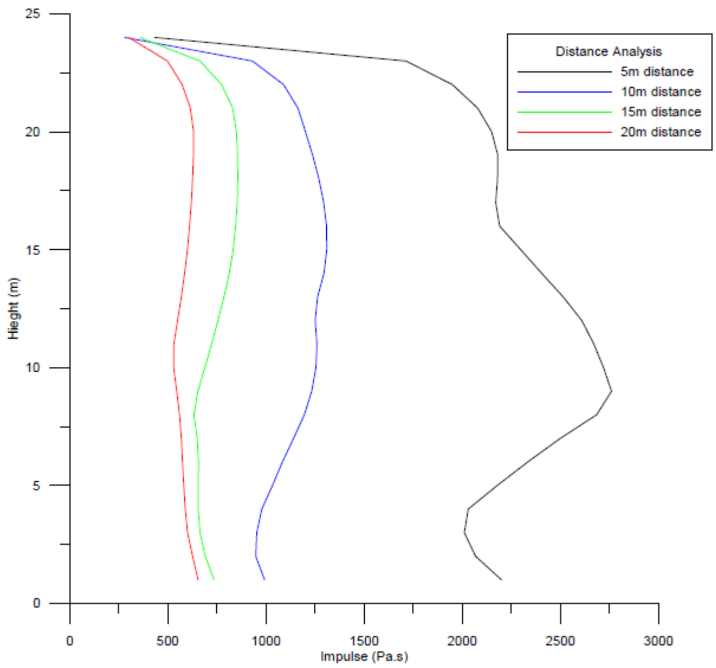


Figure 6.14. Impulses on building (5m wall).

The reduction of impulses with each 5m increase in distance for the analyses with no walls, 2m walls, 3m walls, 4m walls, and 5m walls are presented in Tables B.1-B.5 in Appendix B. For instance, in the case of no wall, if a distance of 10m is present between the blast wall and building instead of 5m, then the impulses on the first meter of the building reduces by 59.8% as seen in Table B.1. This reduction effect decreased slightly on higher elevations of the building façade as it is given in the Tables B.1-B.5. As the wall height increased, the advantages of adding the extra stand-off distance also decreased.

In Figures 6.15-6.20 impulse vs wall-building distance graphs of six different points at different heights (3m, 6m, 9m, 12m, 15m and 18m) on the building façade are presented. At each point, the exponential decrease of the impulse with increasing distance was observed. Also, at higher elevations, the lines of different walls converge to each other, so it represents the diminishing of protection provided by blast walls at these elevations.

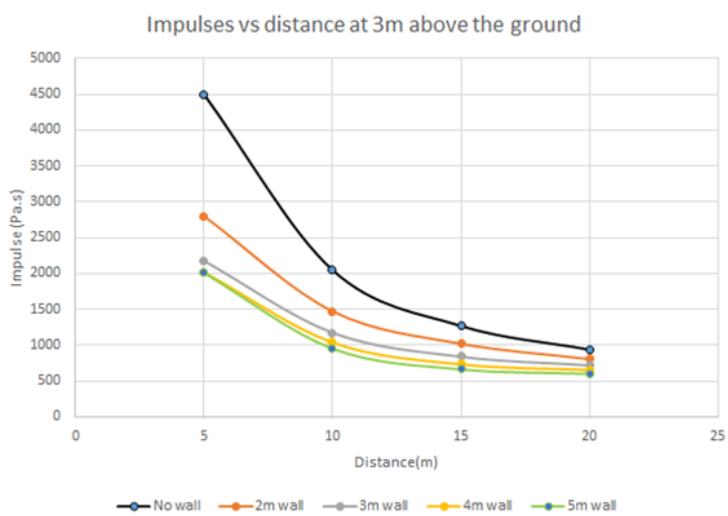


Figure 6.15. Impulse vs Wall-Building Distance at 3m elevation.

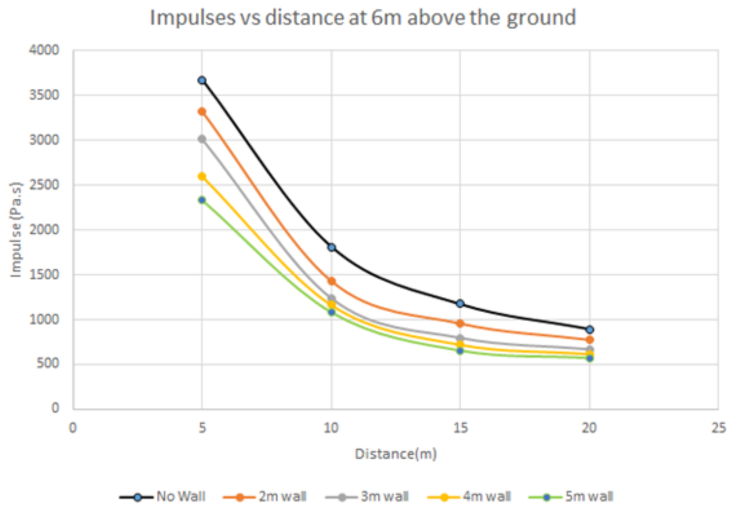


Figure 6.16. Impulse vs Wall-Building Distance at 6m elevation.

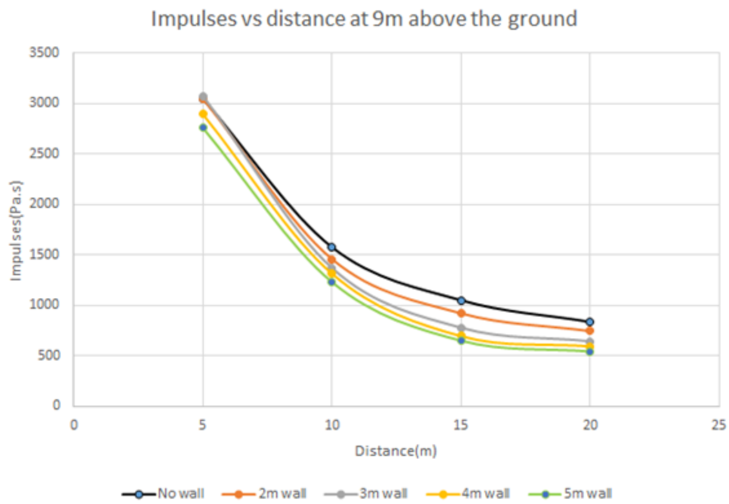


Figure 6.17. Impulse vs Wall-Building Distance at 9m elevation.

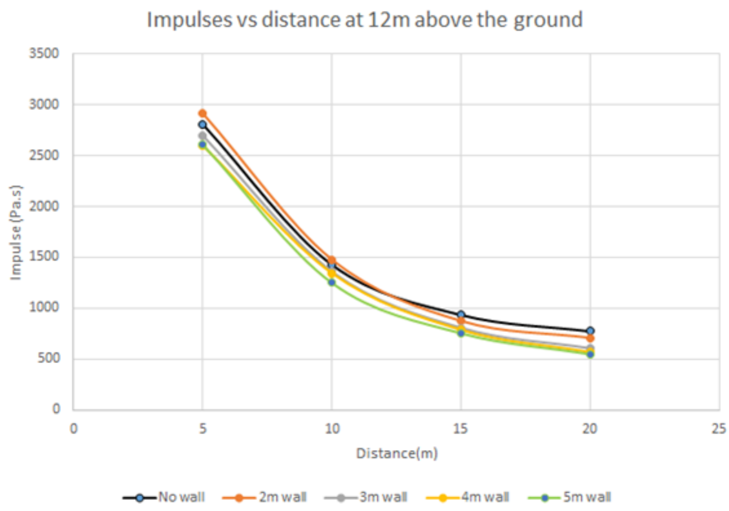


Figure 6.18. Impulse vs Wall-Building Distance at 12m elevation.

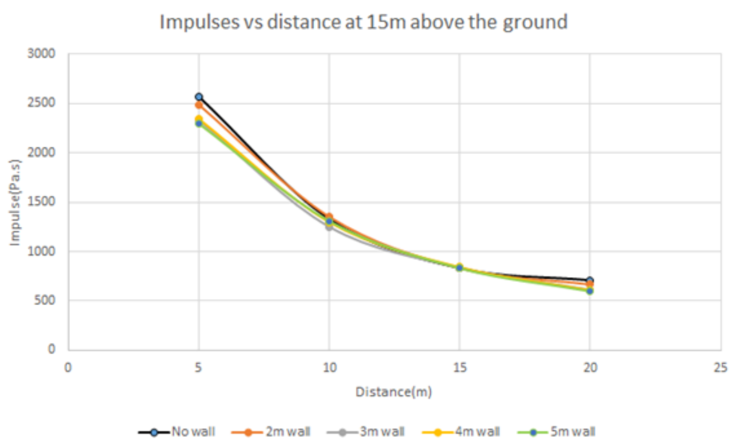


Figure 6.19. Impulse vs Wall-Building Distance at 15m elevation.

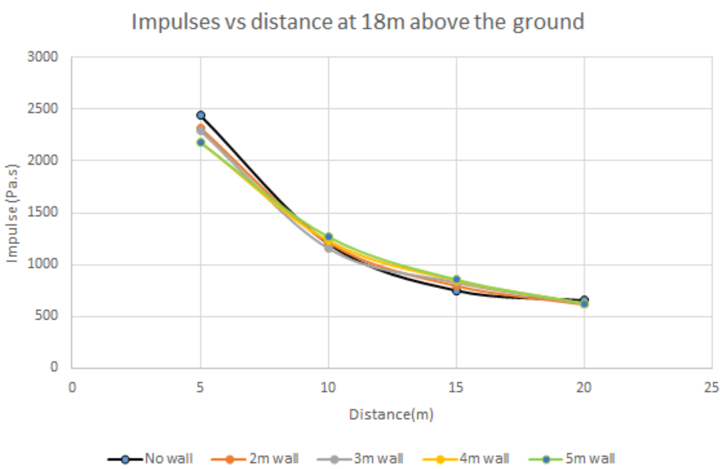


Figure 6.20. Impulse vs Wall-Building Distance at 18m elevation.

7. SUMMARY AND CONCLUSIONS

There were 20 different analyses conducted using the Air3D tool. Pressures on the building after an explosion scenario and the effects of the two main parameters in blast loading were examined.

It was concluded that as the distance between the wall and building increased, the protection area of the blast wall also increased. However, the reduction in the impulses was decreased, meaning that in large stand-off distances more of the façade area was protected, but the protection amount was smaller.

Thus, as the distance between the wall and the building increased, the impulses due to blast reduced, but in a descending way. For instance, between the standoff distances of 5m and 10m, the reductions in the impulses were large. On the other hand, if 15m distance and 20m distance analyses were considered, the difference of the provided protection was relatively small.

Blast walls provided protection against blast the loads, especially within their heights. Then, as the higher points on the building were examined, the provided advantages decreased, and at some higher elevations, it was reversed.

This reverse effect can be explained by the fact that the blast wall reduced the energy level of the waves, but it also created a redirected wave, so that the initial contact point of the shock wave was elevated. This may not affect a small building. For instance, a 15m building may get only the advantages of the blast wall. However, in the case of a tall, slender building, this effect should definitely be taken into consideration.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

In this study, 2D analyses were made using the Air3D tool. The Air3D tool is also capable of solving 3D simulations. Therefore, a study in 3D can be conducted to verify the results of this study. In 3D simulations, the shock waves also travel along the width of the building and continue to propagate to the sides of the building. Thus, this effect may change the calculated pressures and impulses.

Furthermore, the parametric study can be extended by taking different blast scenarios with different charge weights. This may result in different impulse reductions since the wave speed would be different. Hence, the interactions of different shock waves would be different.

Another future study can be done also by taking into account the effects of these calculated pressures and impulses on the building. LS-Dyna is a sophisticated tool to have these kinds of analyses in which the deformations can be considered. The results of the LS-Dyna analyses can be compared with the Air3D results to have a validation study, and the deformations caused by these pressures and impulses can be simulated for further understanding of the blast wave damage on deformable structures.

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APPENDIX A: PRESSURE TIME HISTORIES OF POINTS ON THE BUILDING FAÇADE

In this appendix, the results of the analyses presented for each point on the building. The graphs of pressure time histories from the analyses with the similar wall-building distances can be seen below:

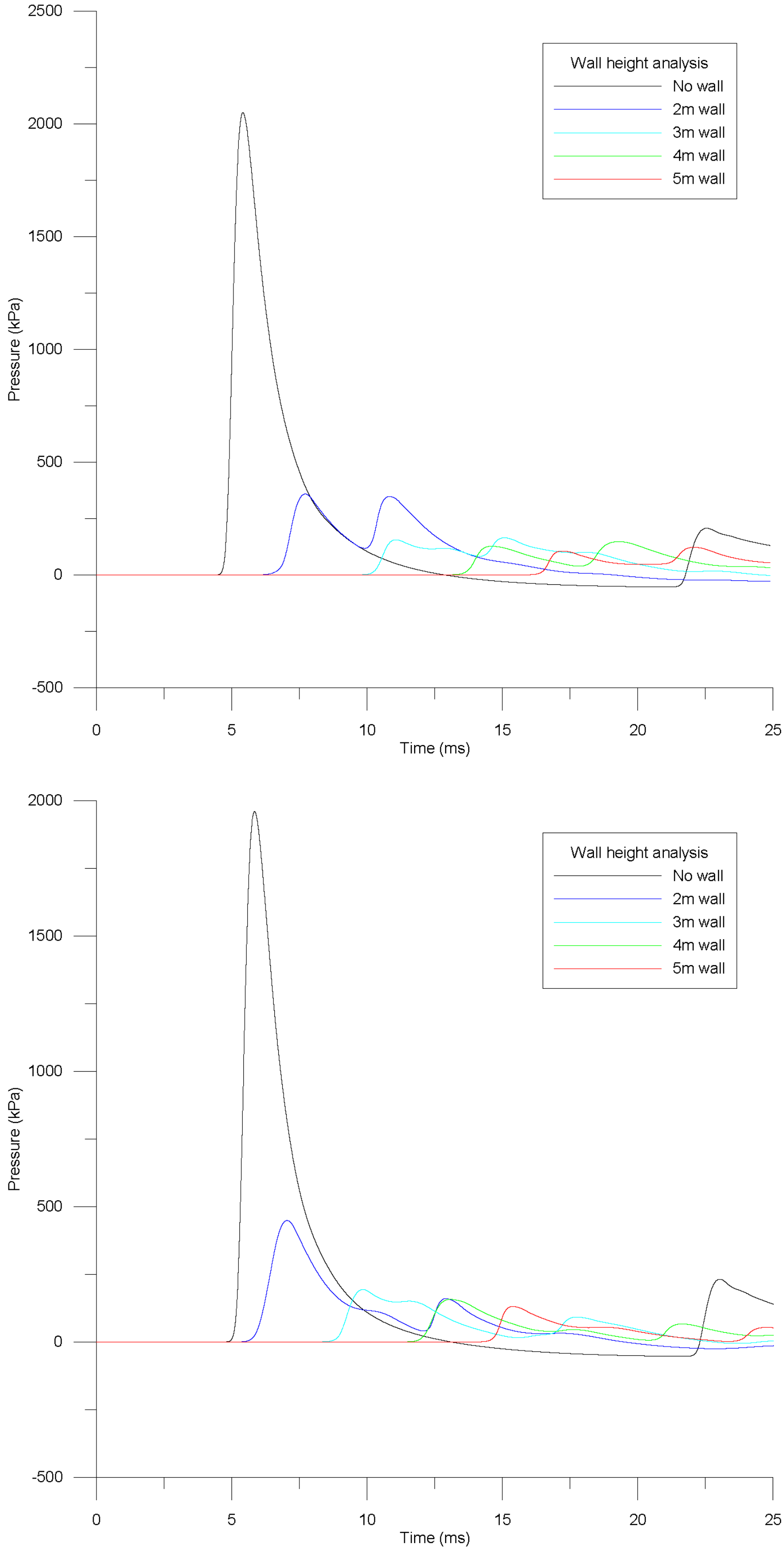


Figure A.1. Pressures on point 1(1m above the ground, top chart), and on point 2(2m above the ground, bottom chart) - 5m wall-building distance.

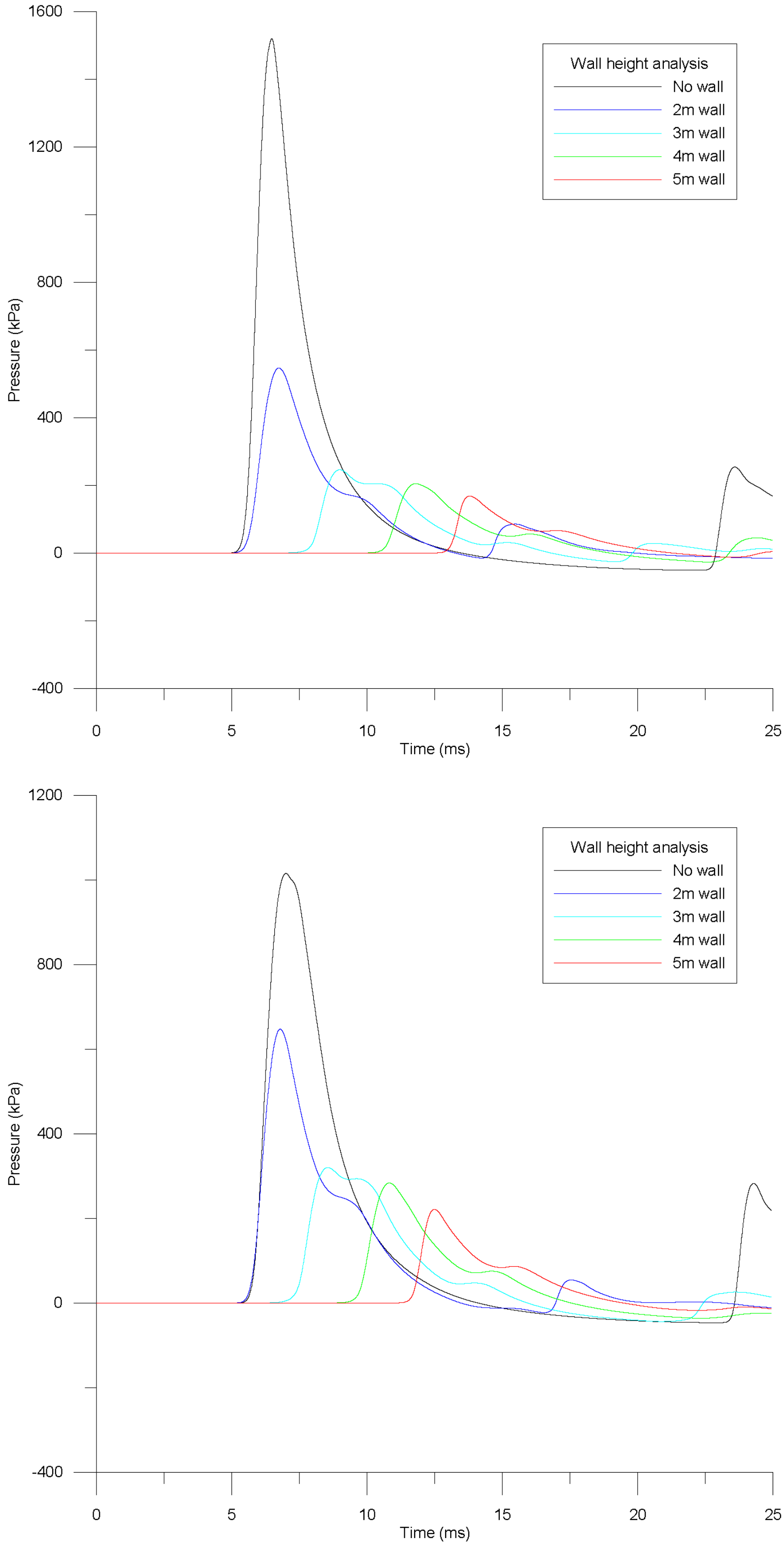


Figure A.2. Pressures on point 3(3m above the ground, top chart), and on point 4(4m above the ground, bottom chart) - 5m wall-building distance.

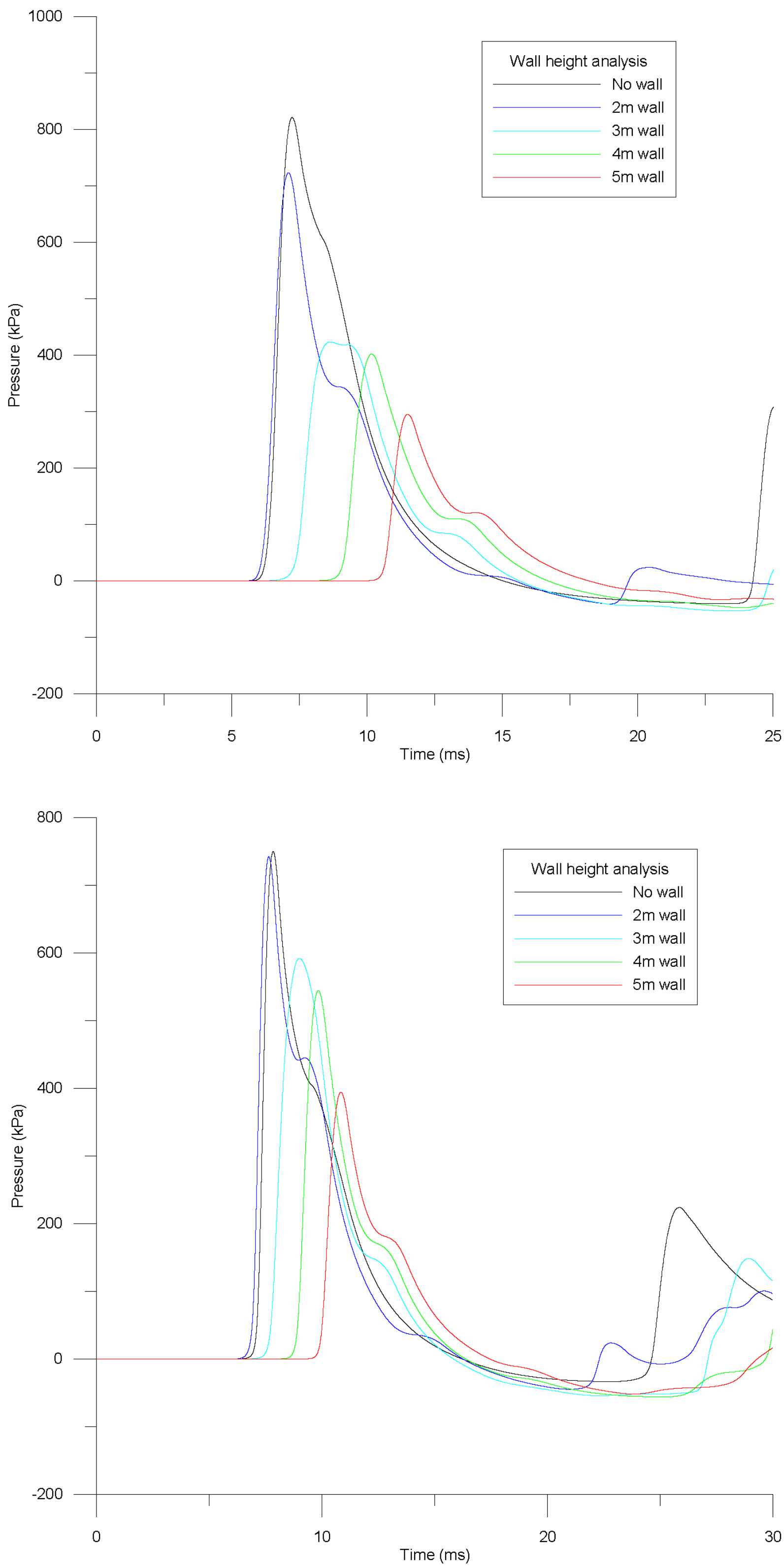


Figure A.3. Pressures on point 5(5m above the ground, top chart), and on point 6(6m above the ground, bottom chart) - 5m wall-building distance.

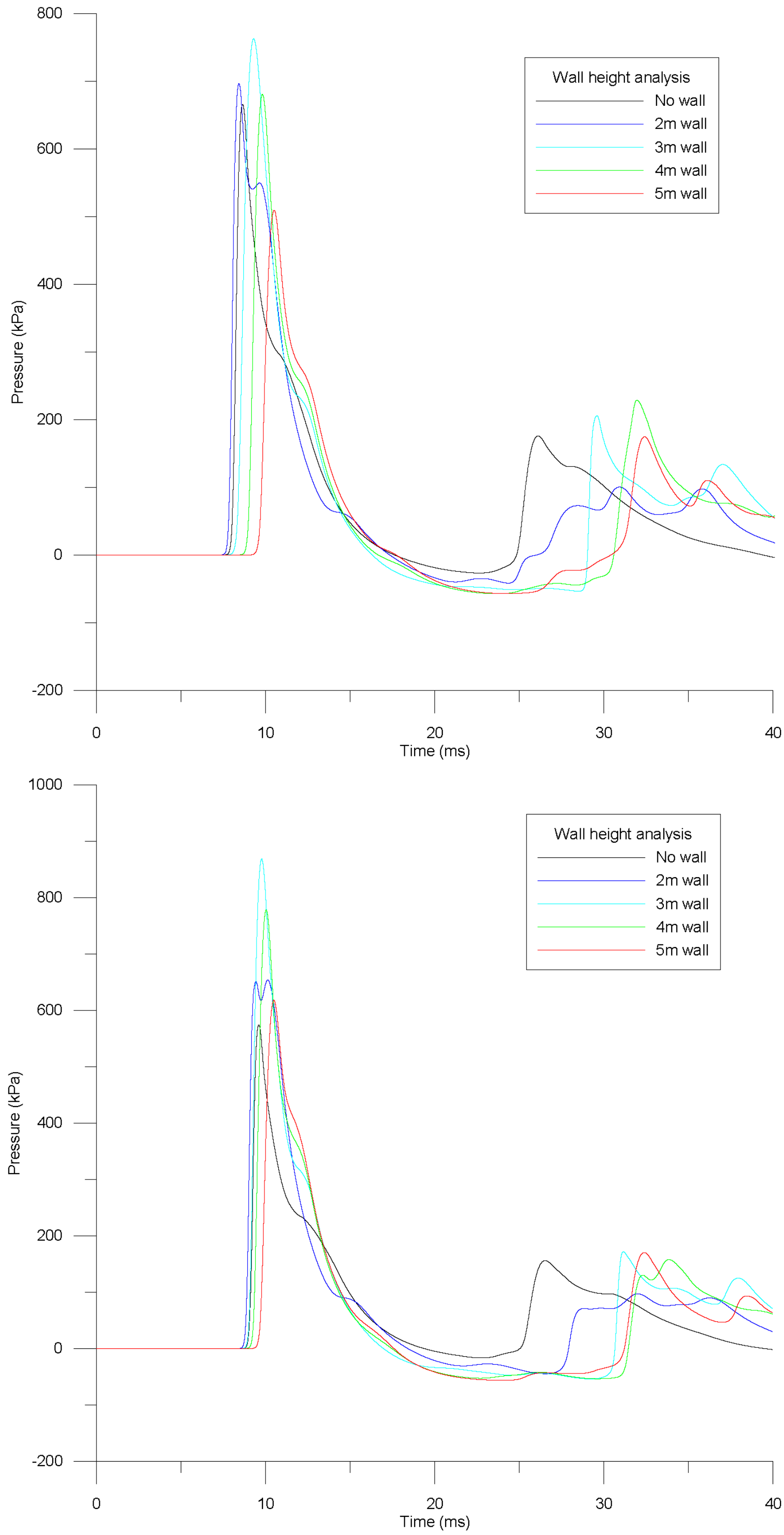


Figure A.4. Pressures on point 7(7m above the ground, top chart), and on point 8(8m above the ground, bottom chart) - 5m wall-building distance.

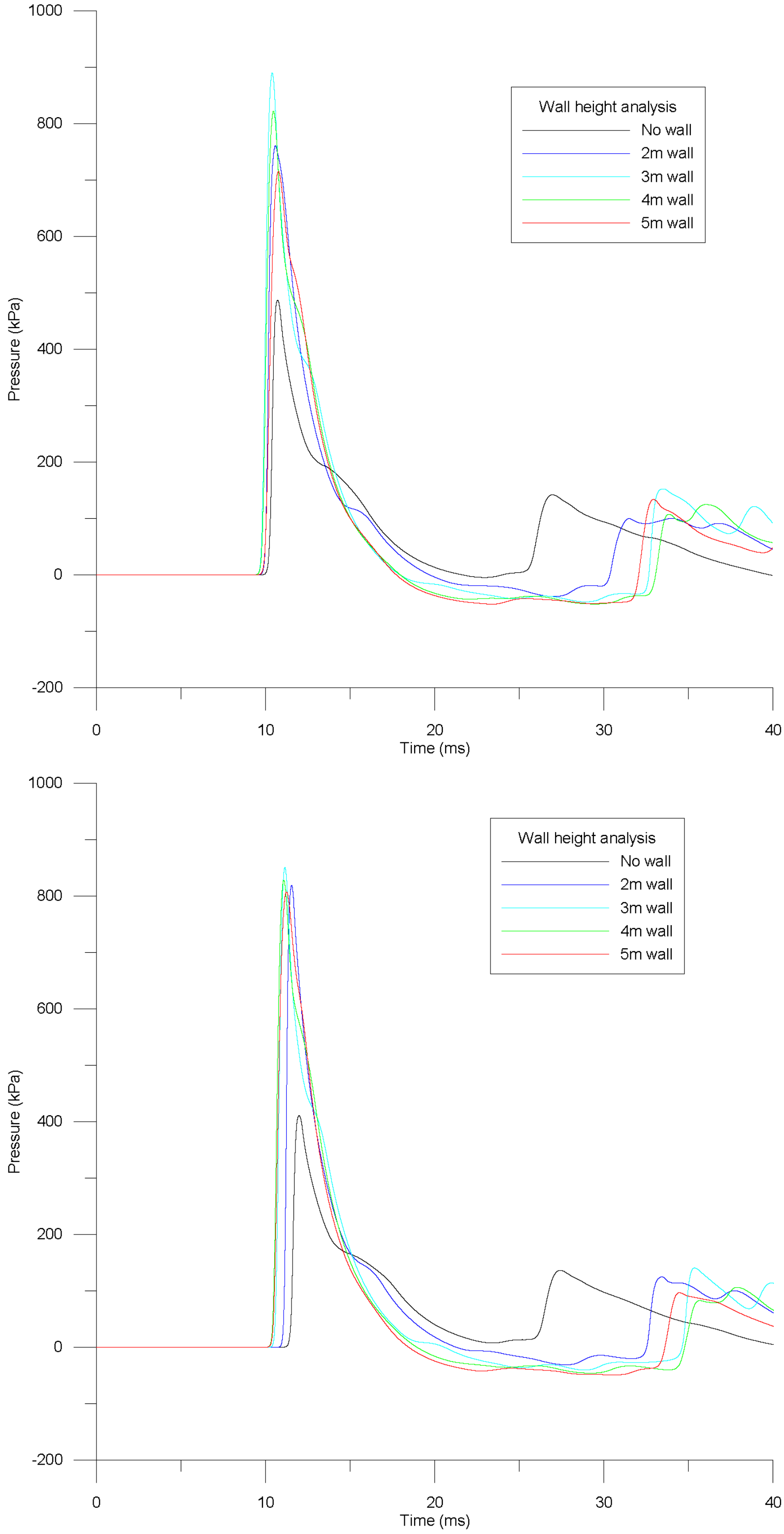
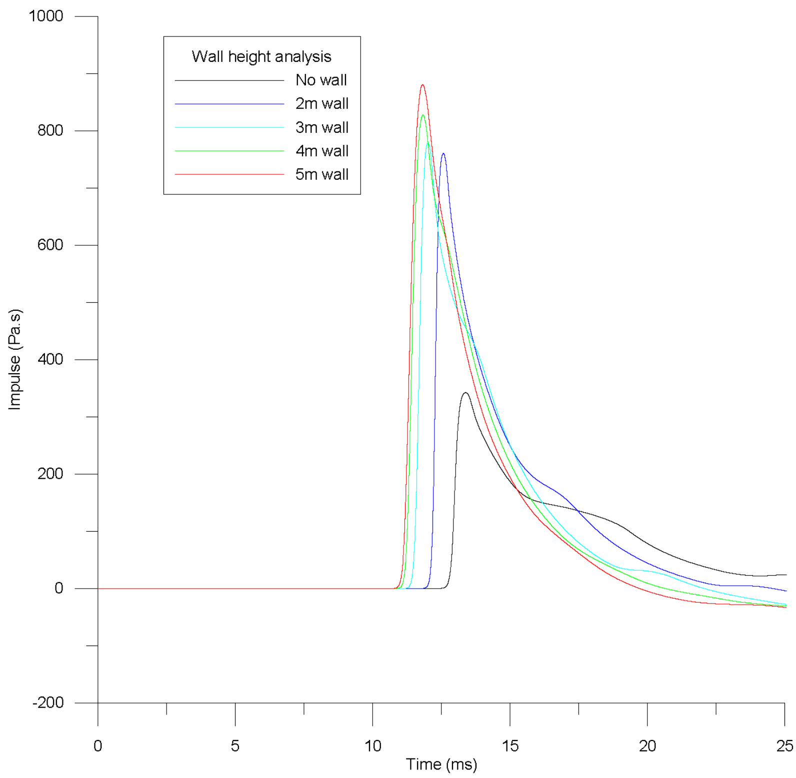


Figure A.5. Pressures on point 9(9m above the ground, top chart), and on point 10(10m above the ground, bottom chart) - 5m wall-building distance.



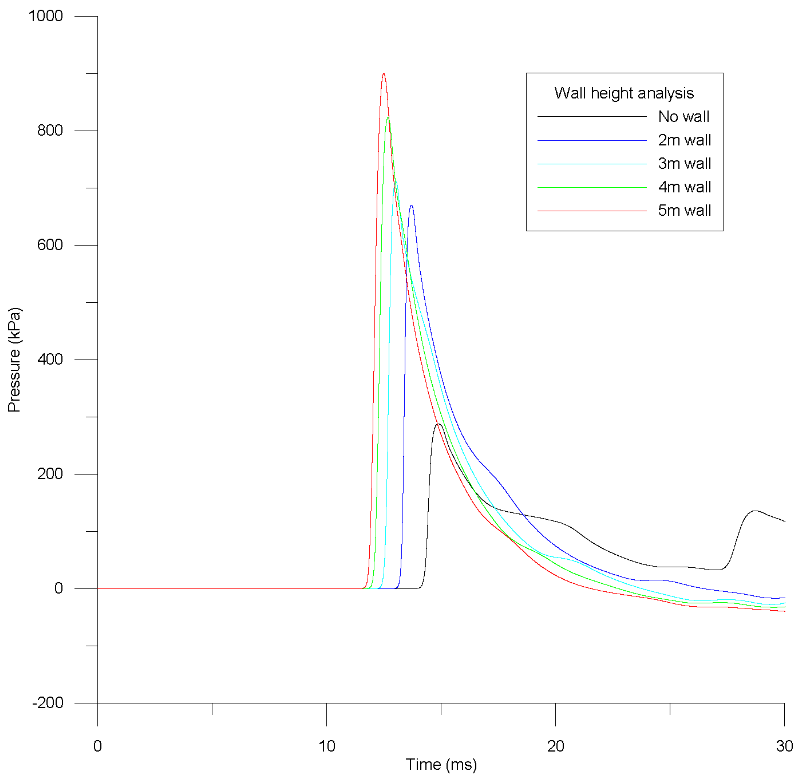


Figure A.6. Pressures on point 11(11m above the ground, top chart), and on point 12(12m above the ground, bottom chart) - 5m wall-building distance.

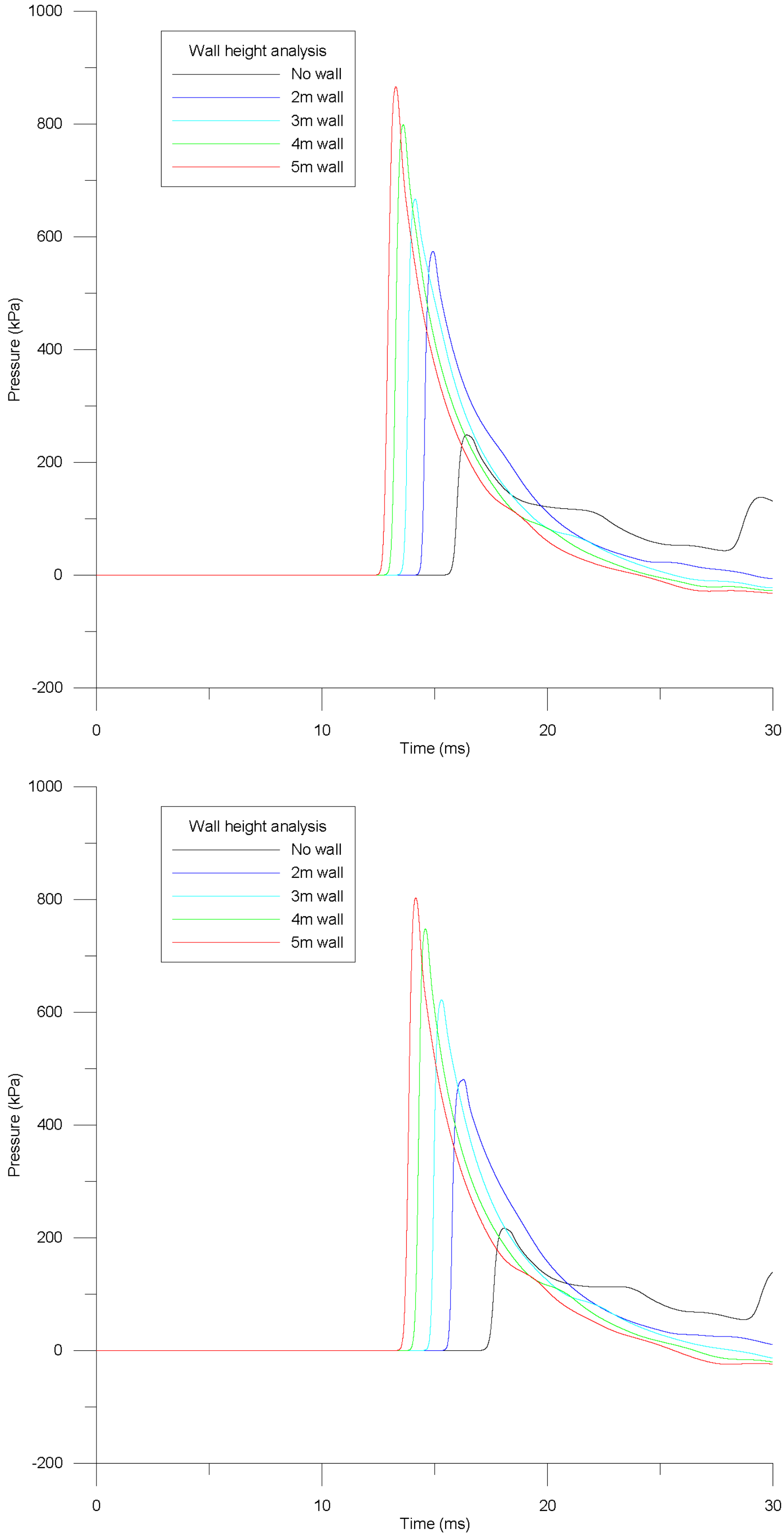
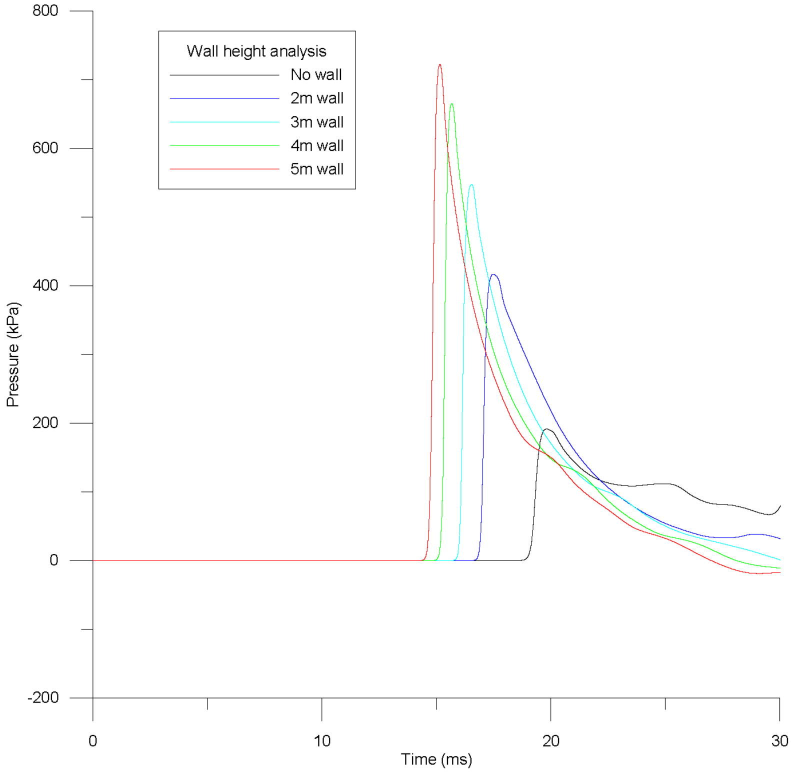


Figure A.7. Pressures on point 13(13m above the ground, top chart), and on point 14(14m above the ground, bottom chart) - 5m wall-building distance.



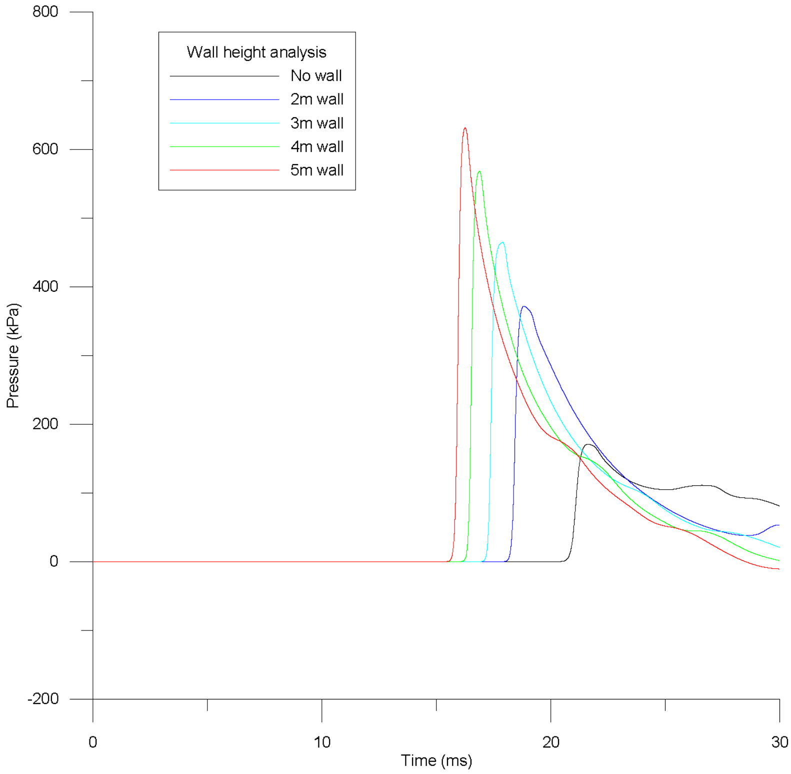


Figure A.8. Pressures on point 15(15m above the ground, top chart), and on point 16(16m above the ground, bottom chart) - 5m wall-building distance.

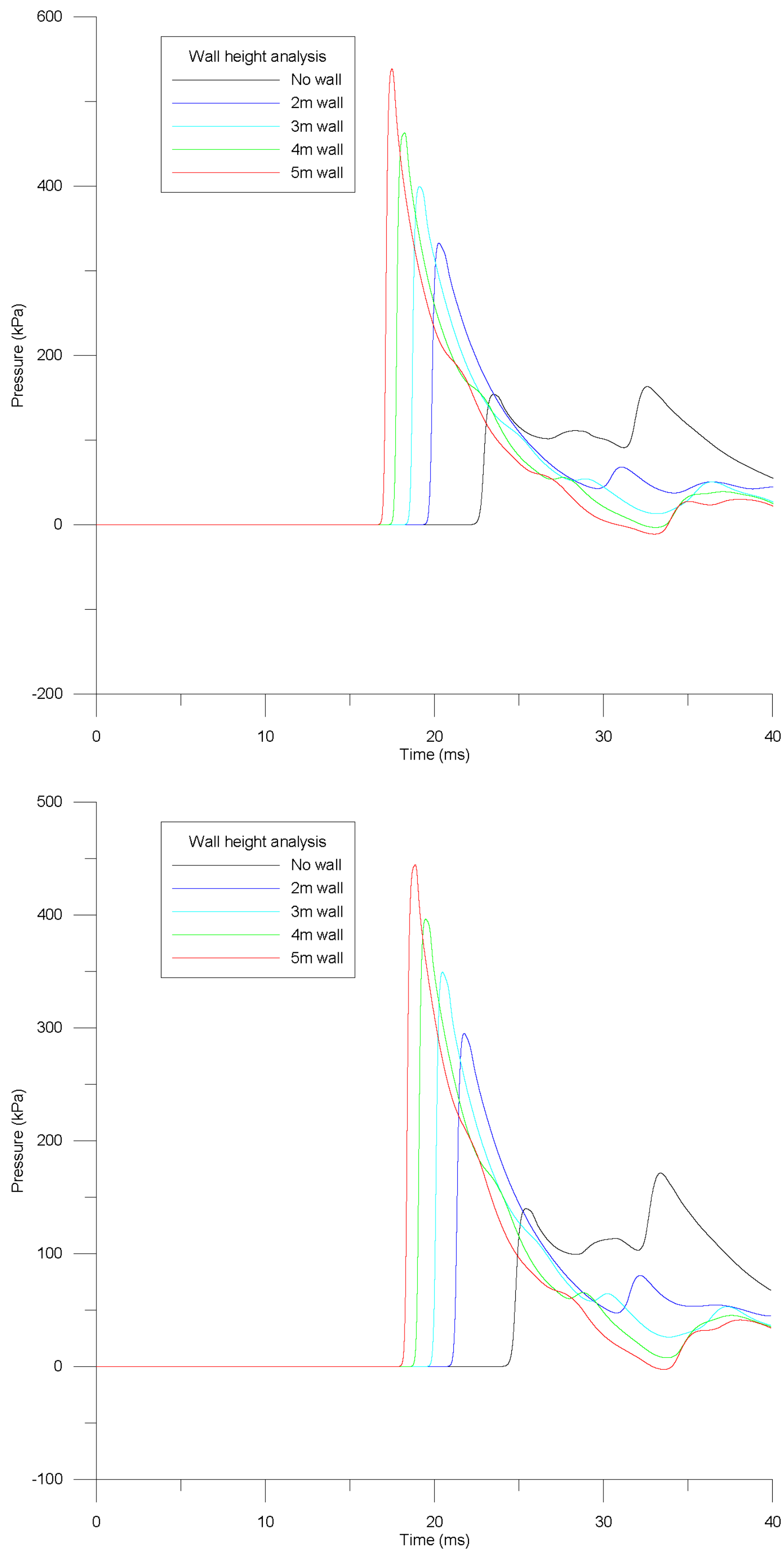
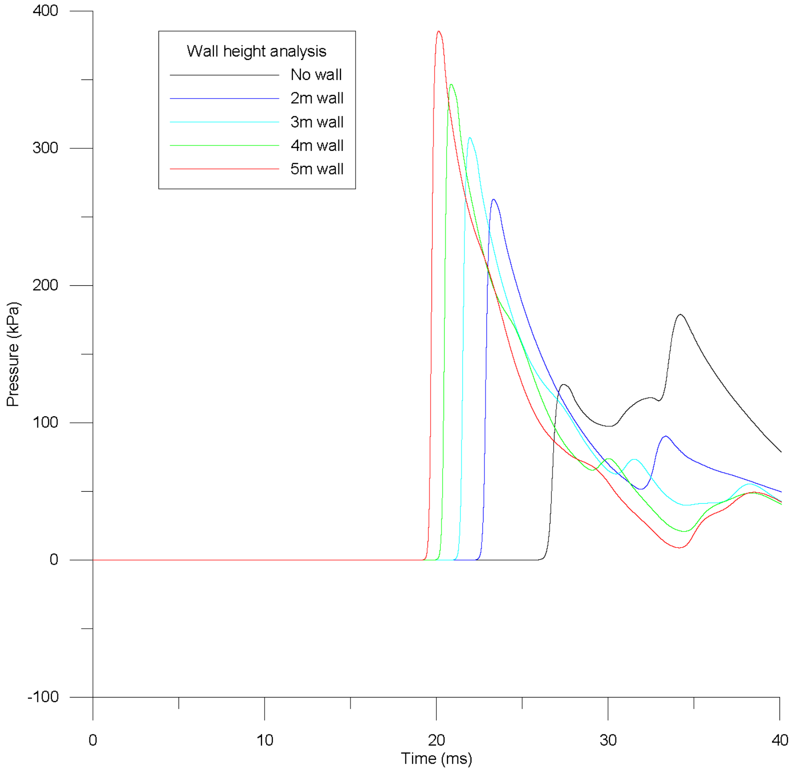


Figure A.9. Pressures on point 17(17m above the ground, top chart), and on point 18(18m above the ground, bottom chart) - 5m wall-building distance.



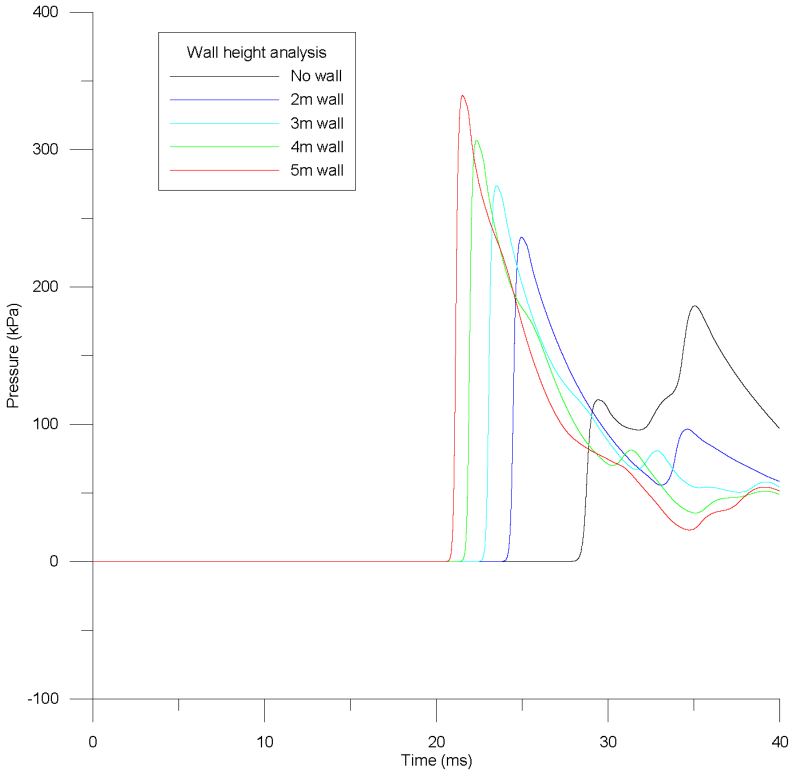


Figure A.10. Pressures on point 19(19m above the ground, top chart), and on point 20(20m above the ground, bottom chart) - 5m wall-building distance.

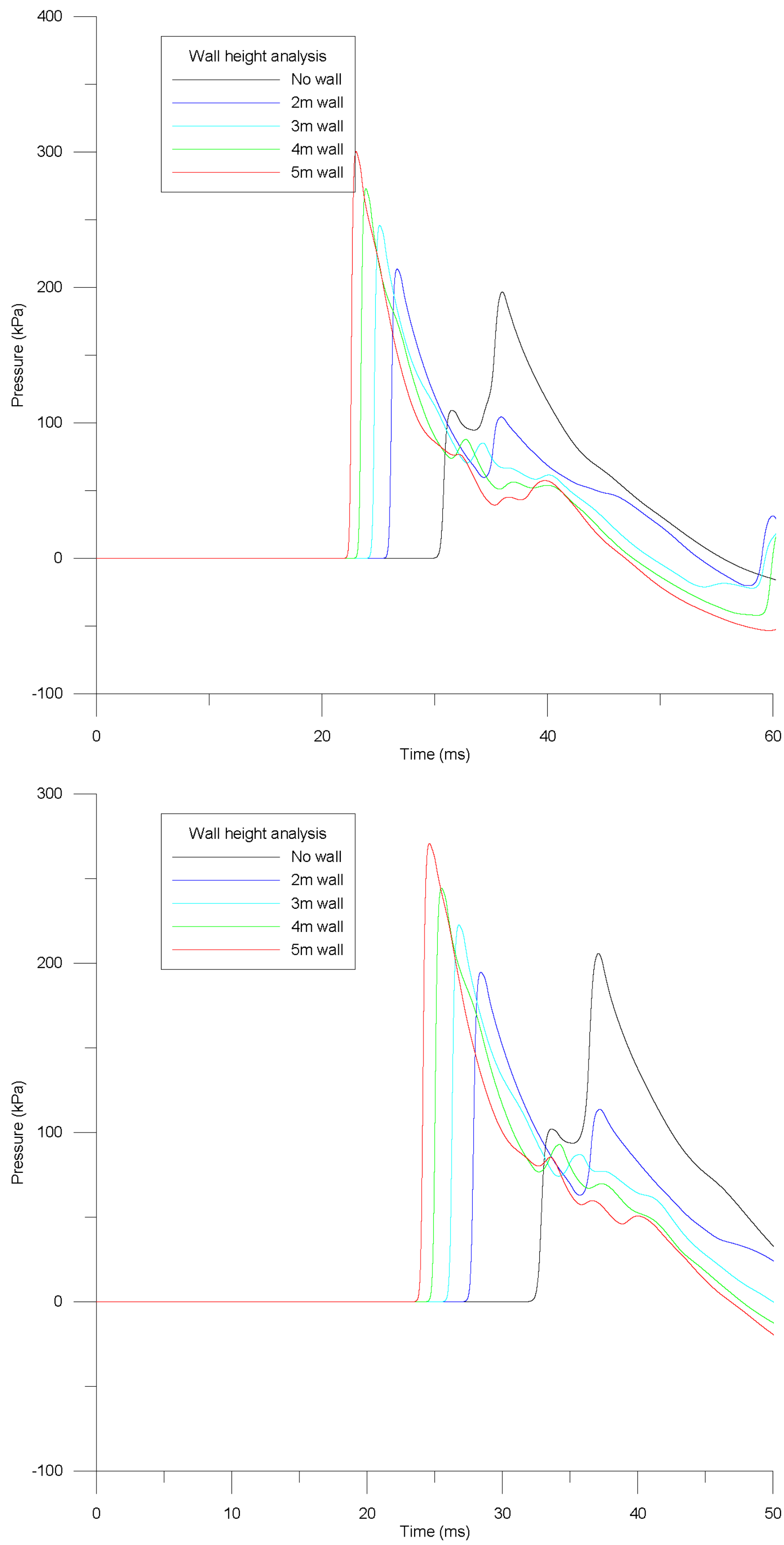
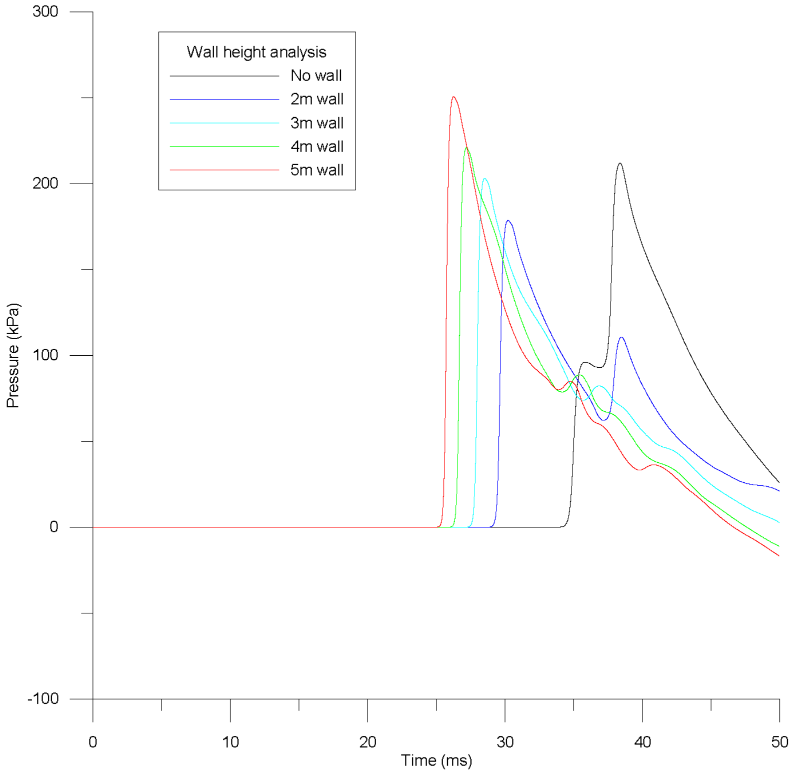


Figure A.11. Pressures on point 21(21m above the ground, top chart), and on point 22(22m above the ground, bottom chart) - 5m wall-building distance.



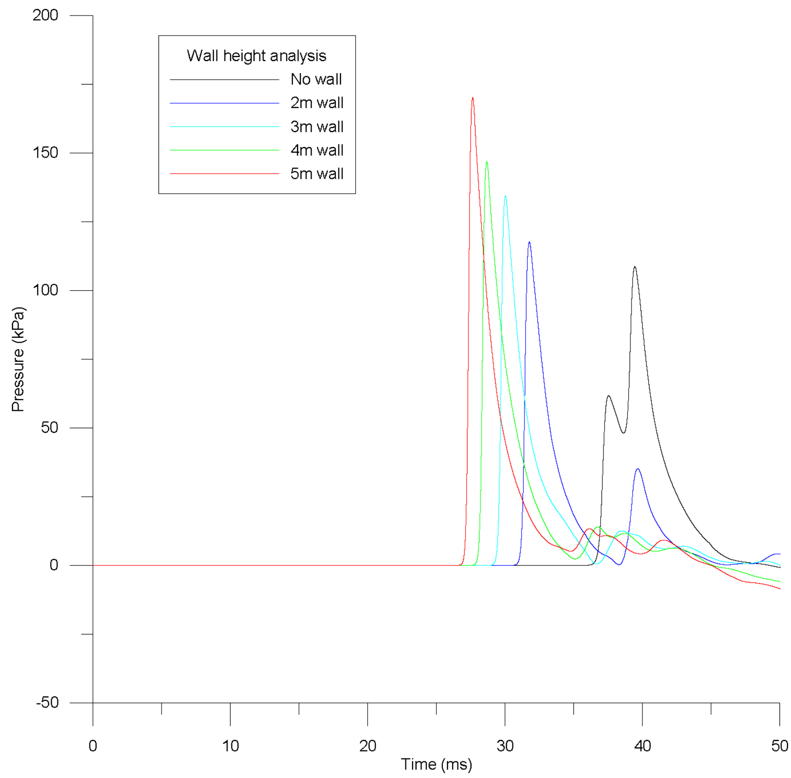


Figure A.12. Pressures on point 23(23m above the ground, top chart), and on point 24(24m above the ground, bottom chart) - 5m wall-building distance.

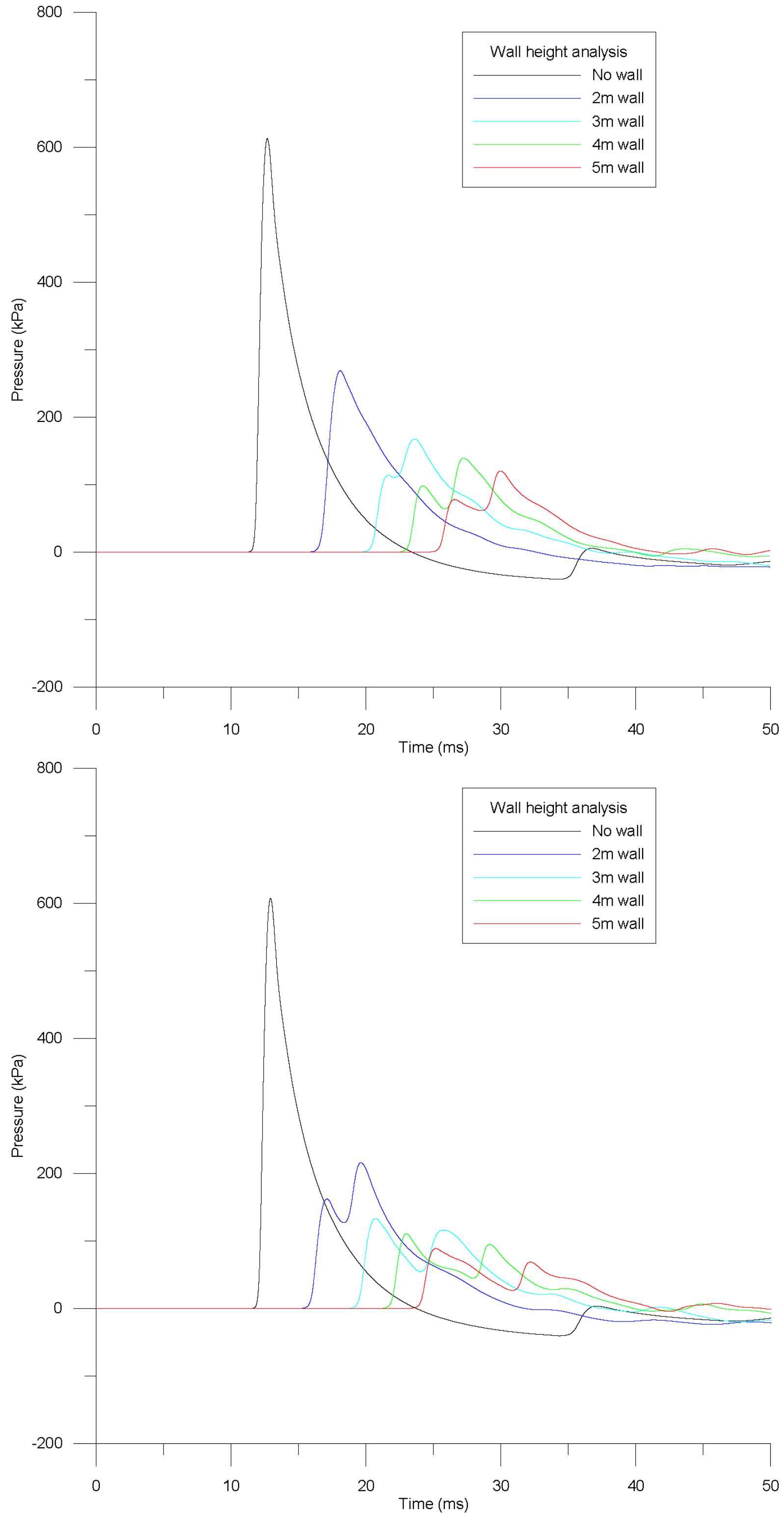
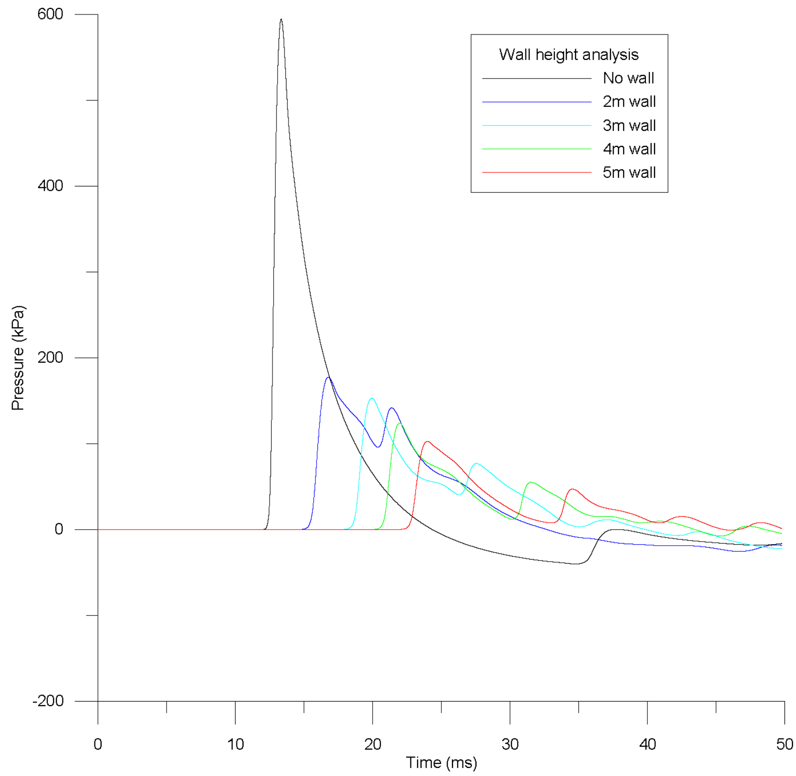


Figure A.13. Pressures on point 1(1m above the ground, top chart), and on point 2(2m above the ground, bottom chart) - 10m wall-building distance.



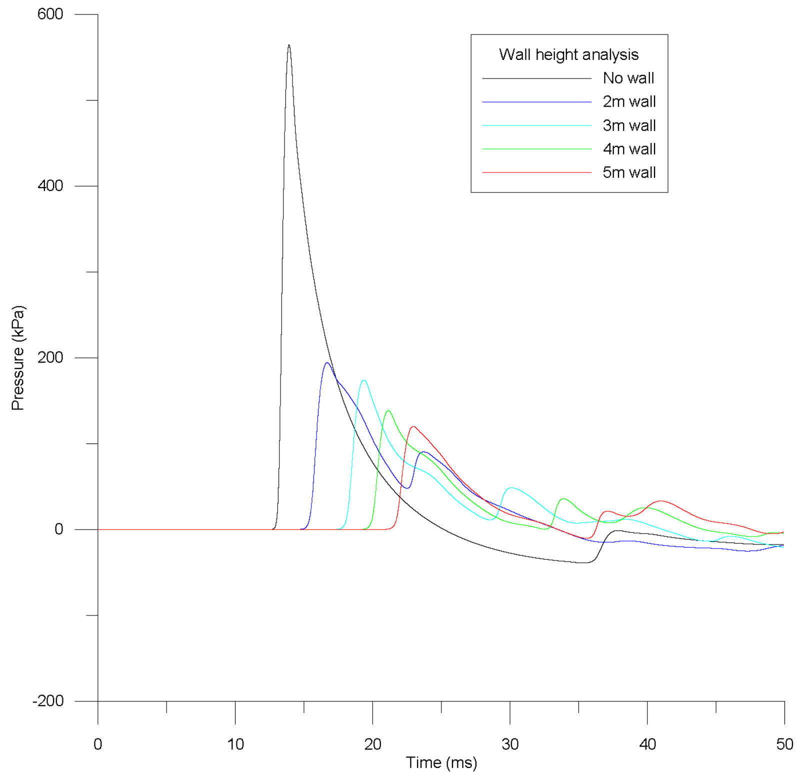


Figure A.14. Pressures on point 3(3m above the ground, top chart), and on point 4(4m above the ground, bottom chart) - 10m wall-building distance.

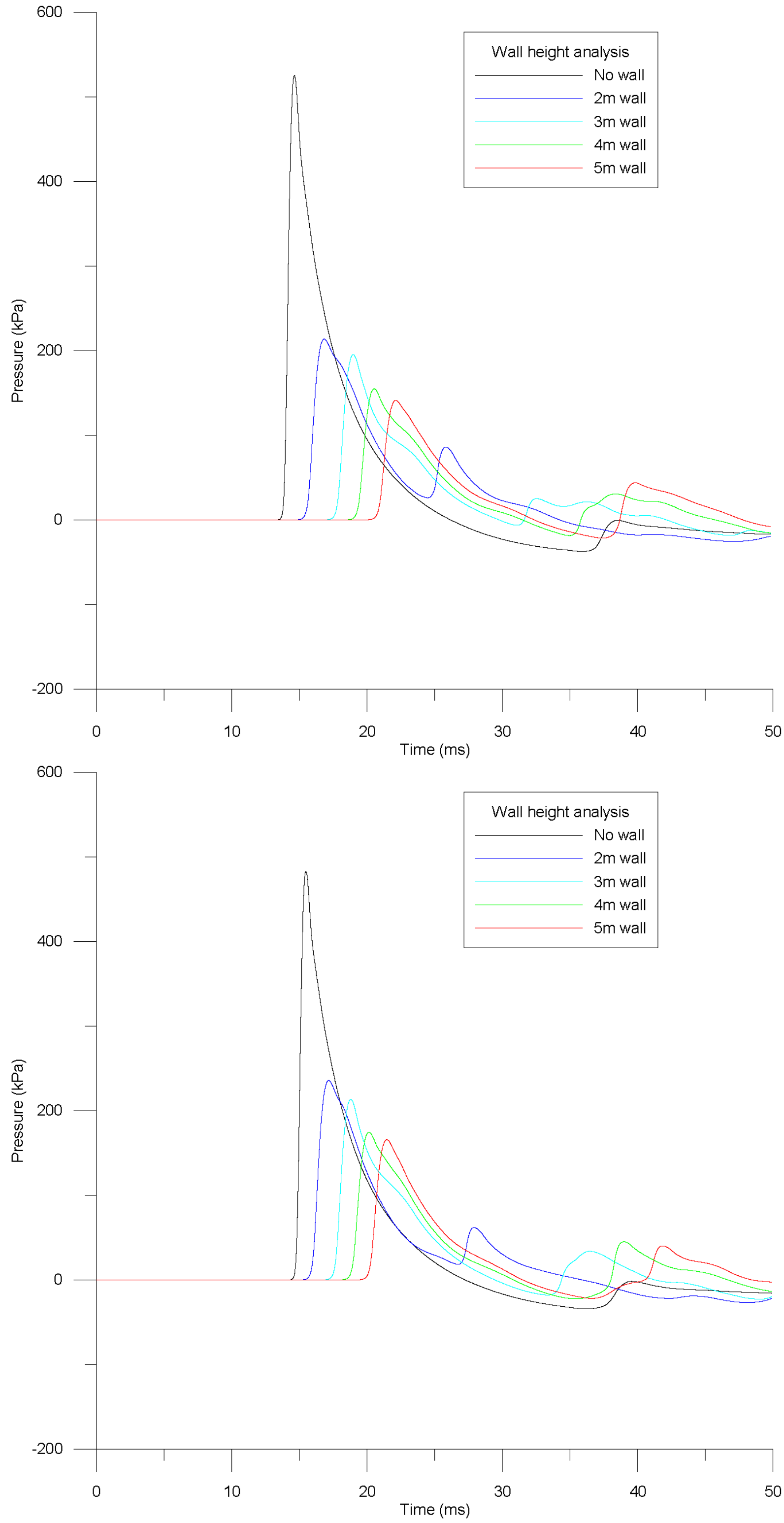


Figure A.15. Pressures on point 5(5m above the ground, top chart), and on point 6(6m above the ground, bottom chart) - 10m wall-building distance.

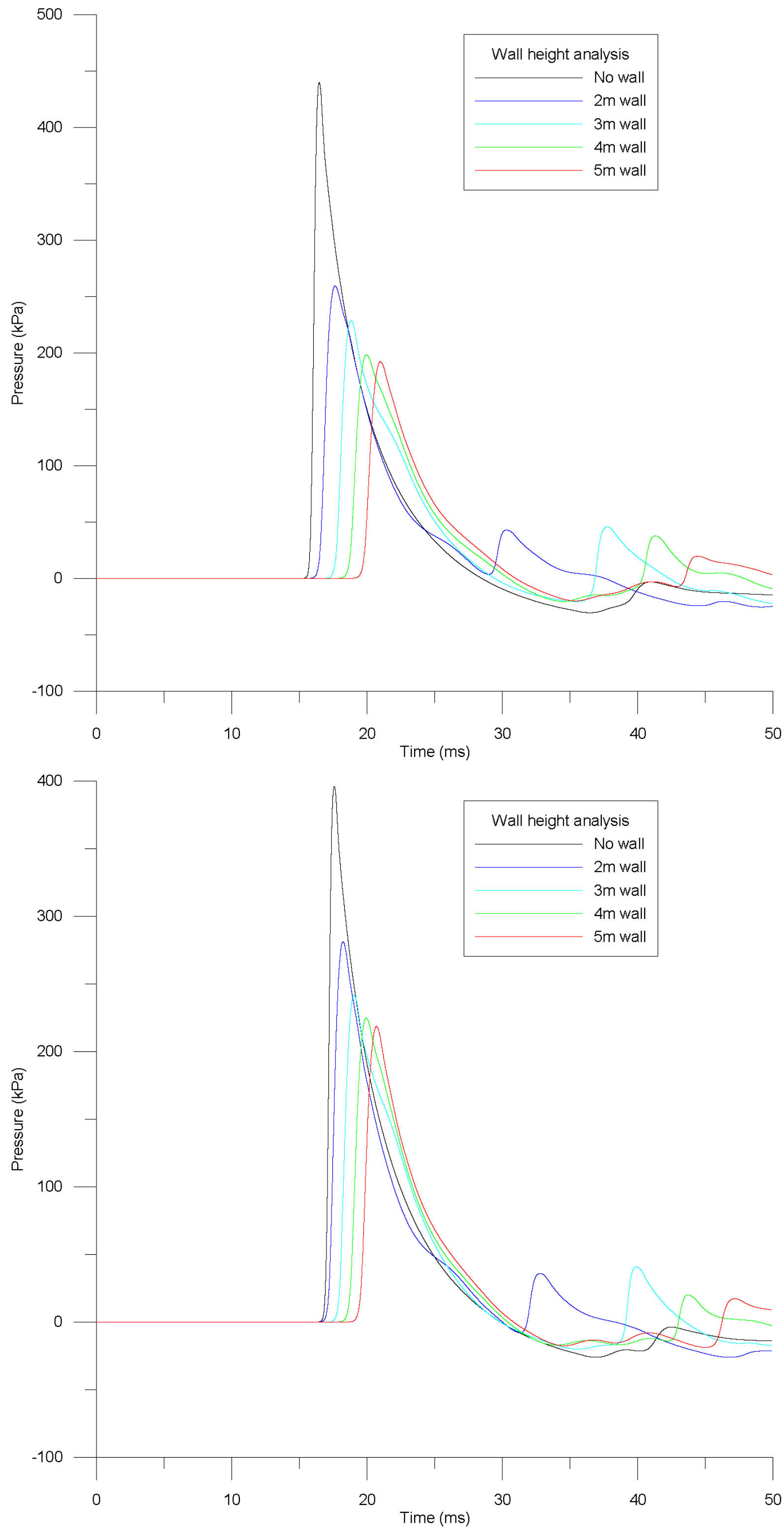


Figure A.16. Pressures on point 7(7m above the ground, top chart), and on point 8(8m above the ground, bottom chart) - 10m wall-building distance.

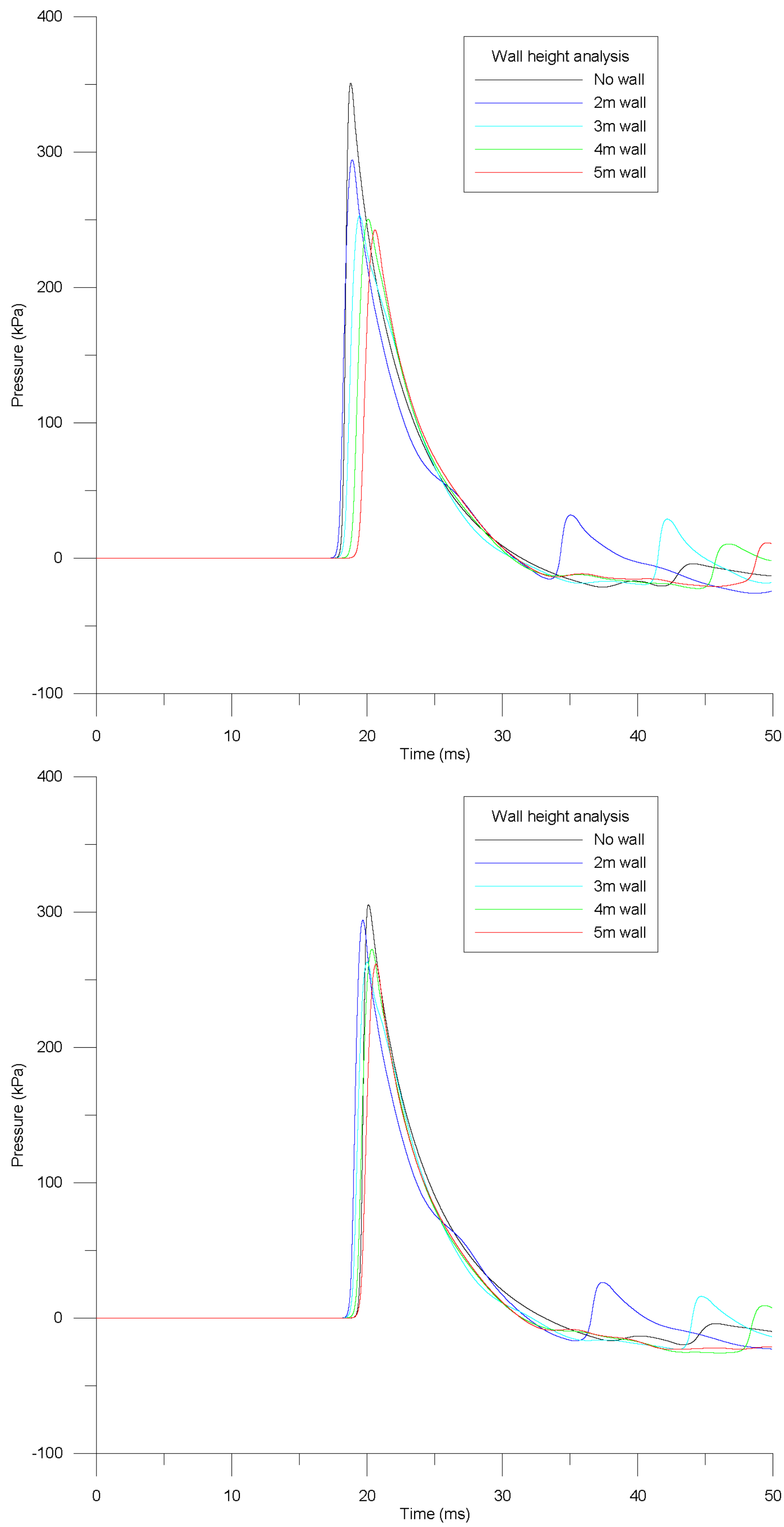


Figure A.17. Pressures on point 9(9m above the ground, top chart), and on point 10(10m above the ground, bottom chart) - 10m wall-building distance.

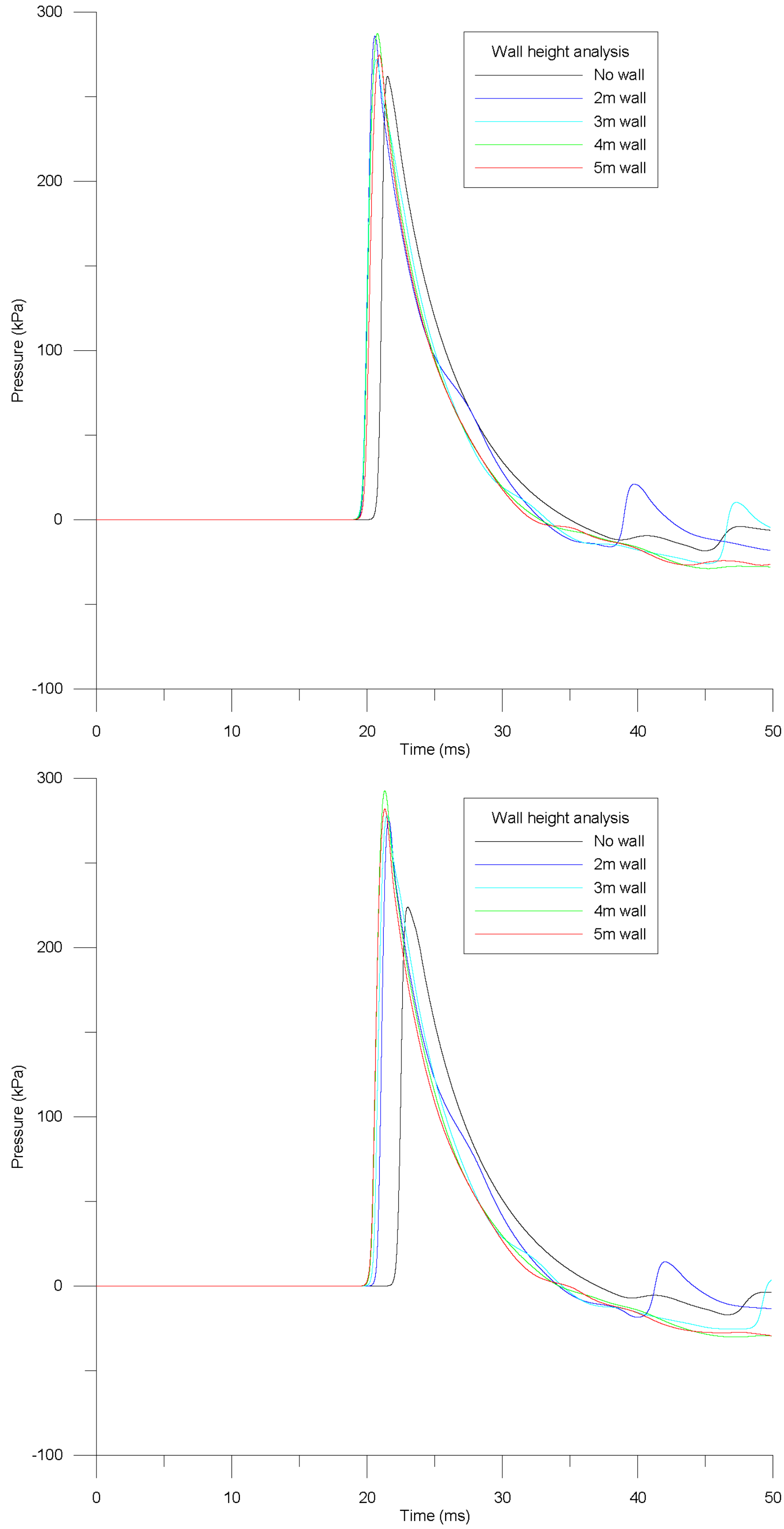


Figure A.18. Pressures on point 11(11m above the ground, top chart), and on point 12(12m above the ground, bottom chart) - 10m wall-building distance.

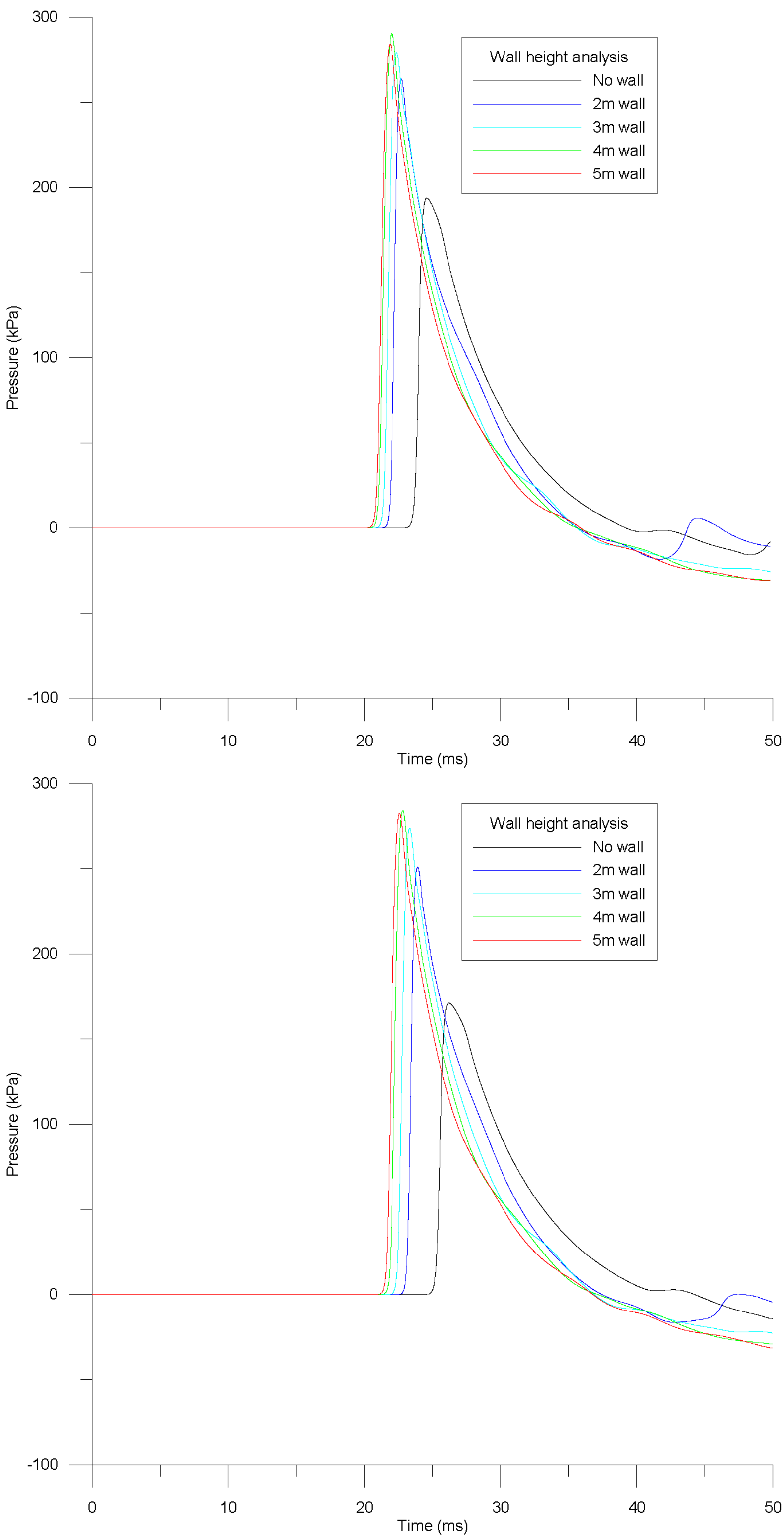
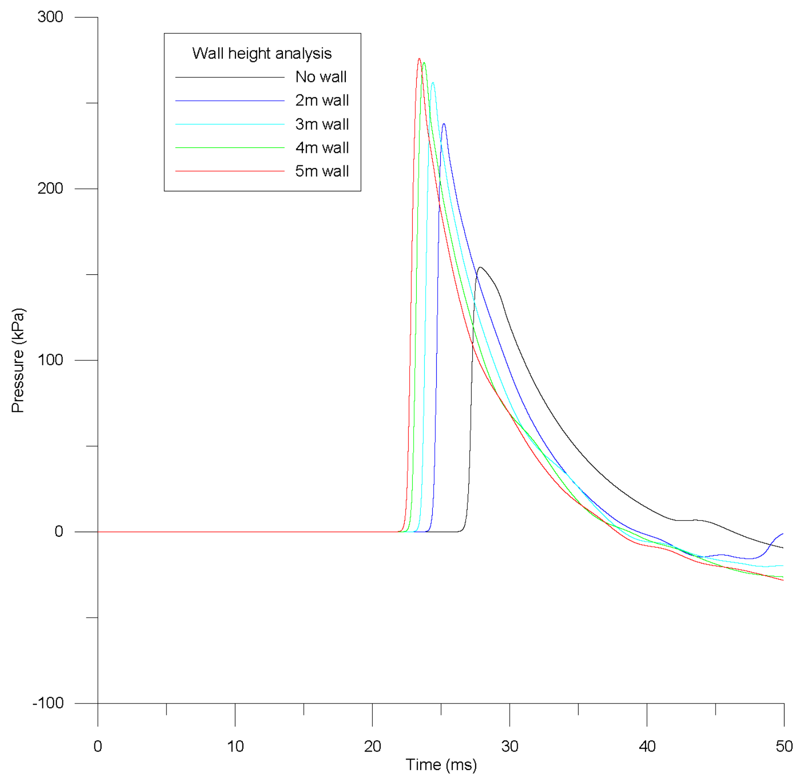


Figure A.19. Pressures on point 13(13m above the ground, top chart), and on point 14(14m above the ground, bottom chart) - 10m wall-building distance.



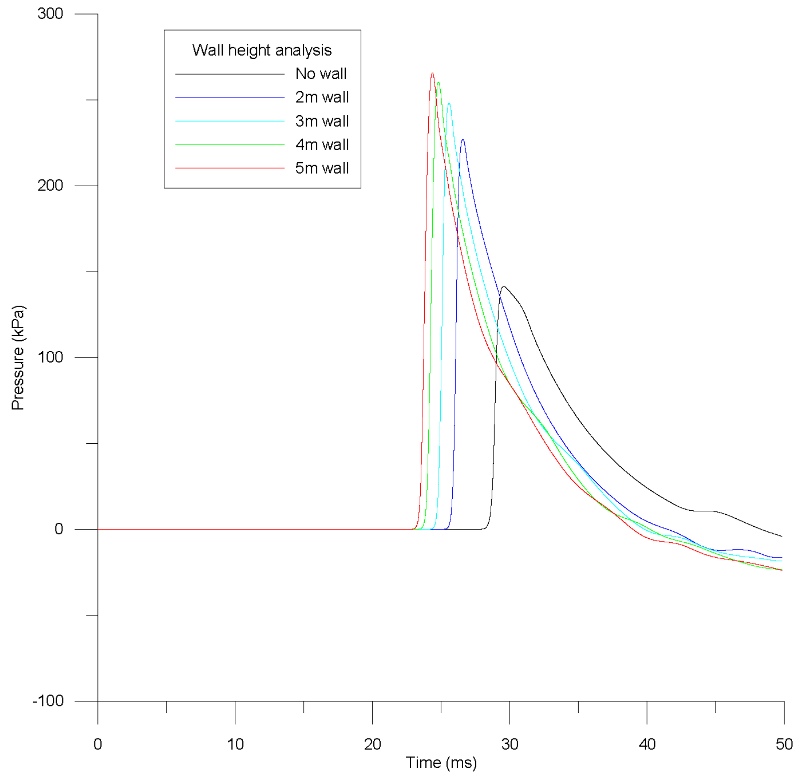


Figure A.20. Pressures on point 15(15m above the ground, top chart), and on point 16(16m above the ground, bottom chart) - 10m wall-building distance.

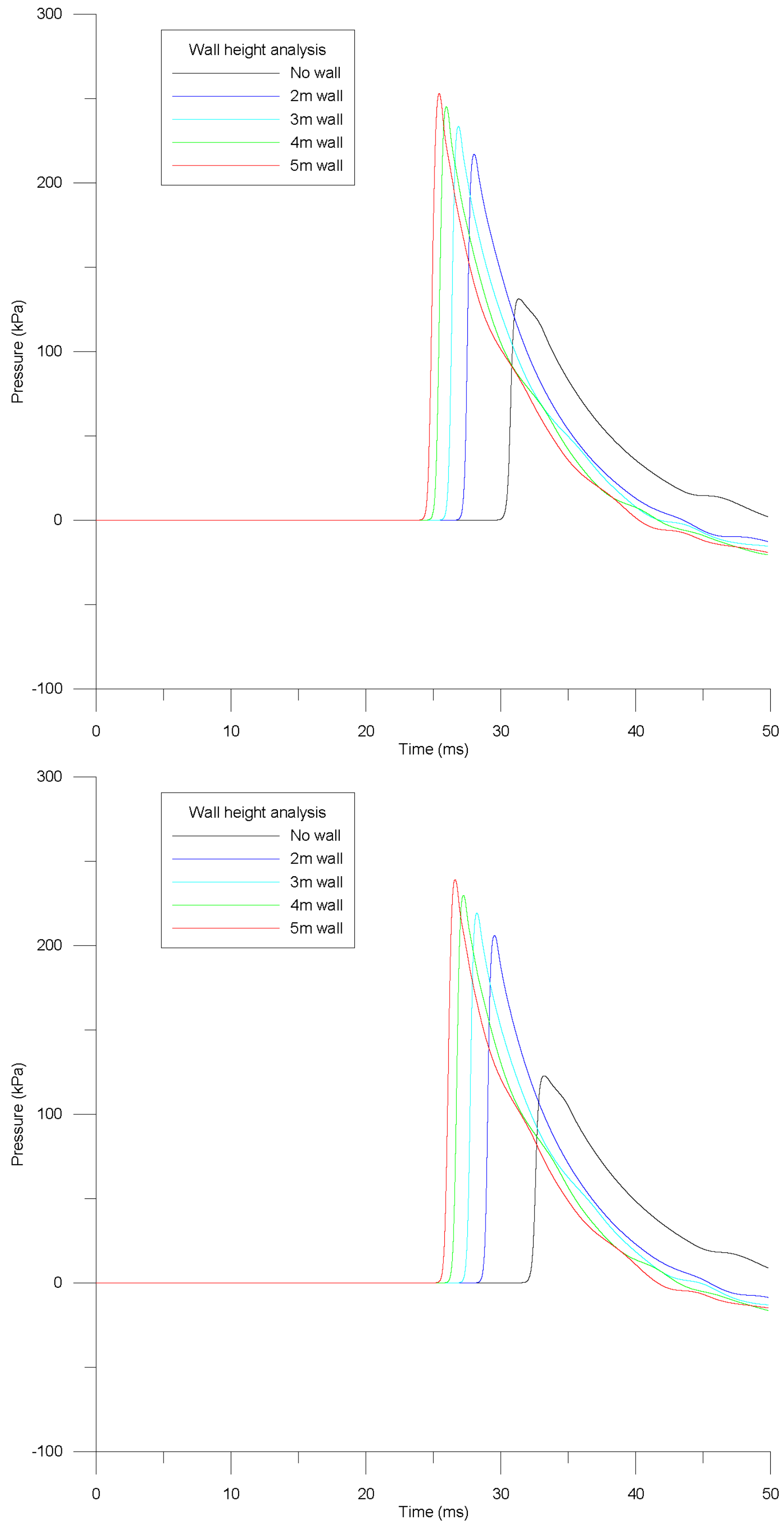


Figure A.21. Pressures on point 17(17m above the ground, top chart), and on point 18(18m above the ground, bottom chart) - 10m wall-building distance.

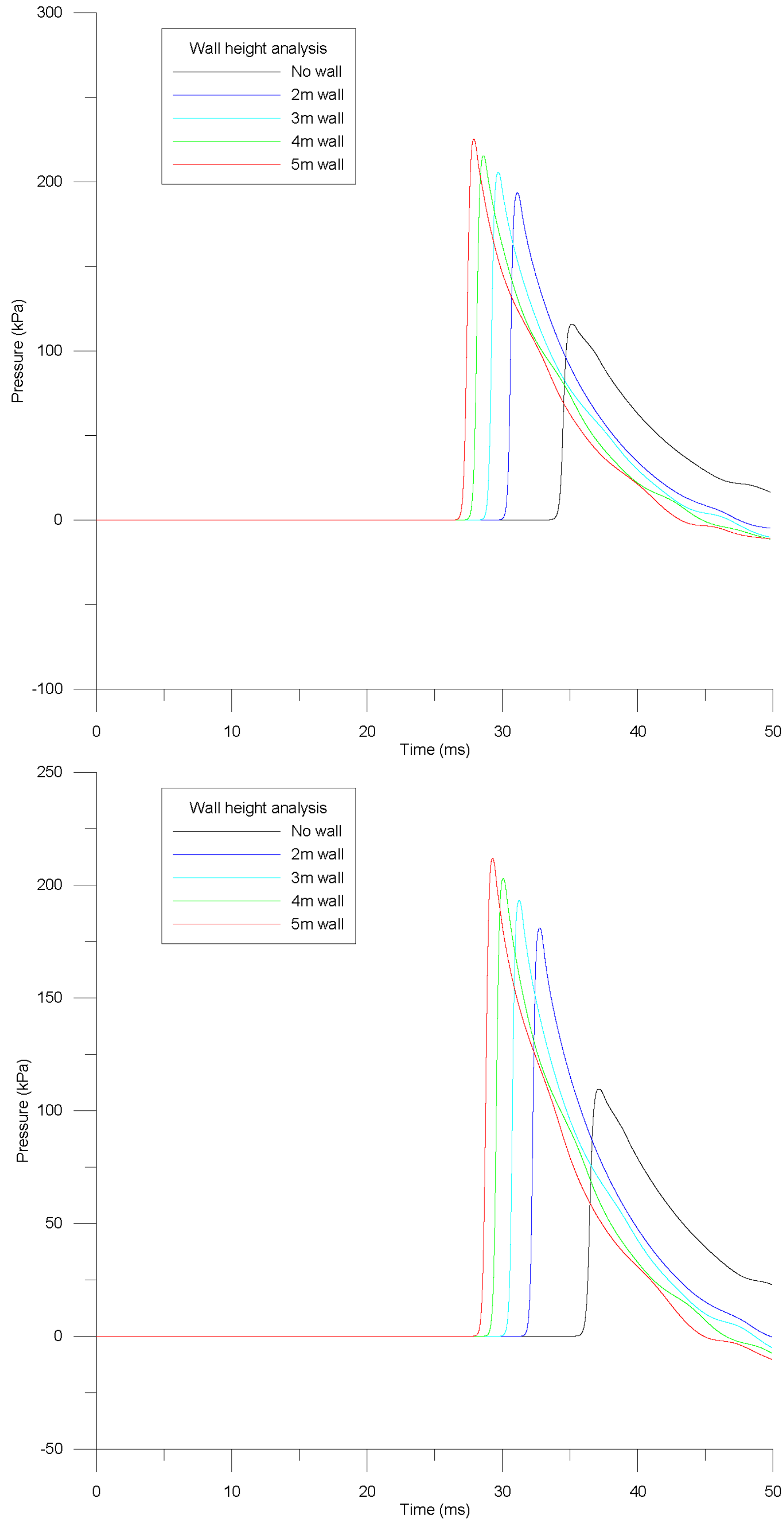


Figure A.22. Pressures on point 19(19m above the ground, top chart), and on point 20(20m above the ground, bottom chart) - 10m wall-building distance.

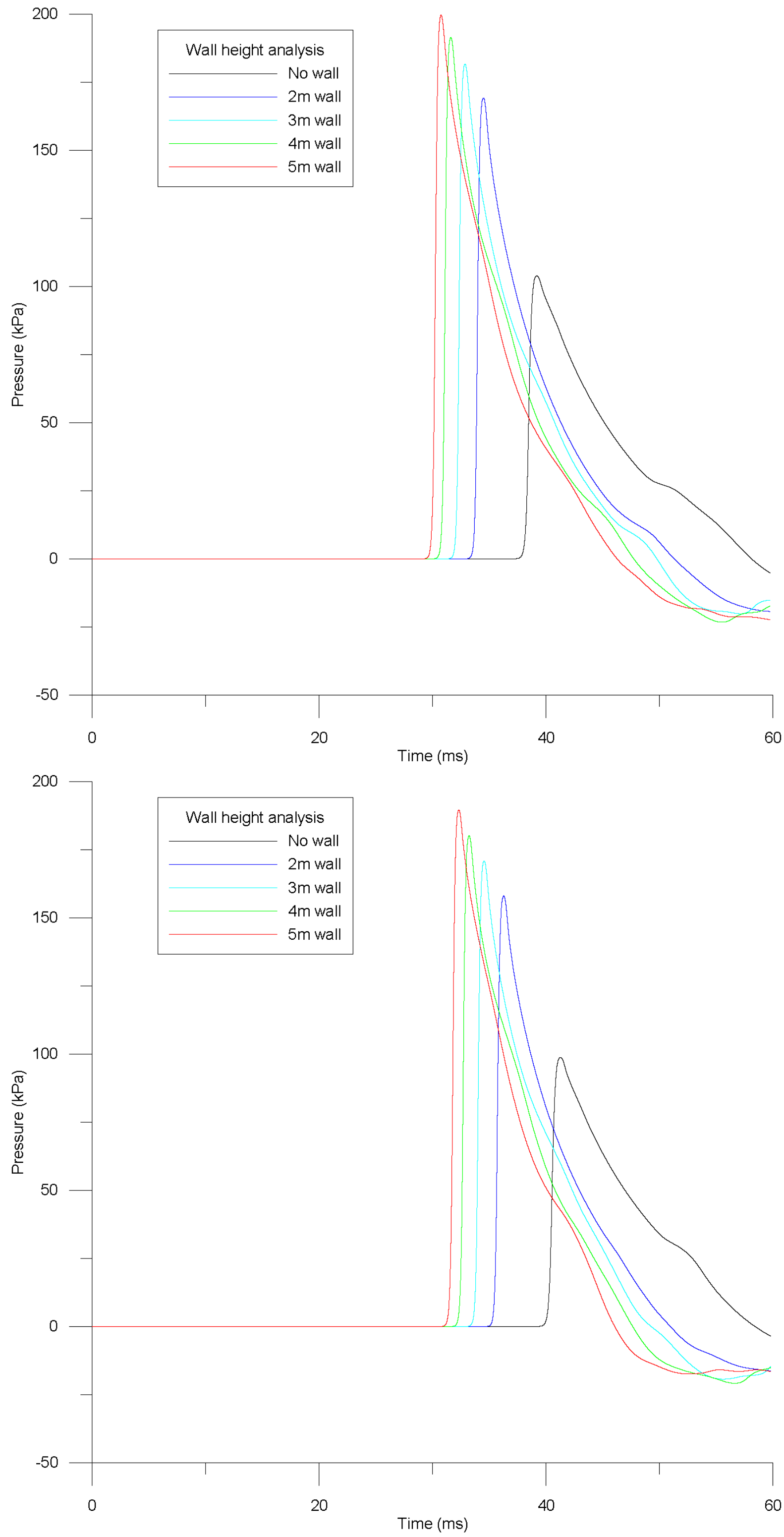


Figure A.23. Pressures on point 21(21m above the ground, top chart), and on point 22(22m above the ground, bottom chart) - 10m wall-building distance.

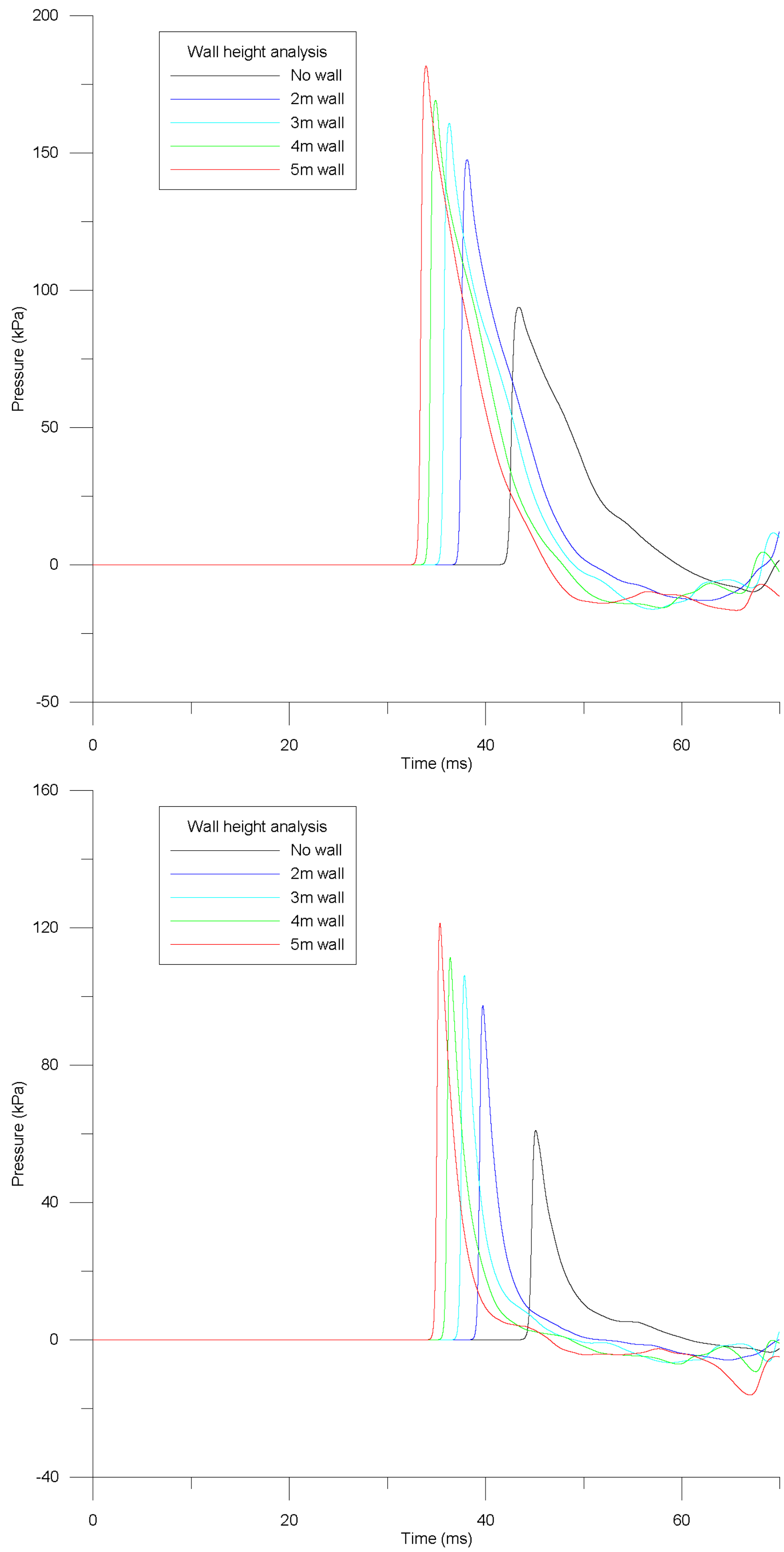


Figure A.24. Pressures on point 23(23m above the ground, top chart), and on point 24(24m above the ground, bottom chart) - 10m wall-building distance.

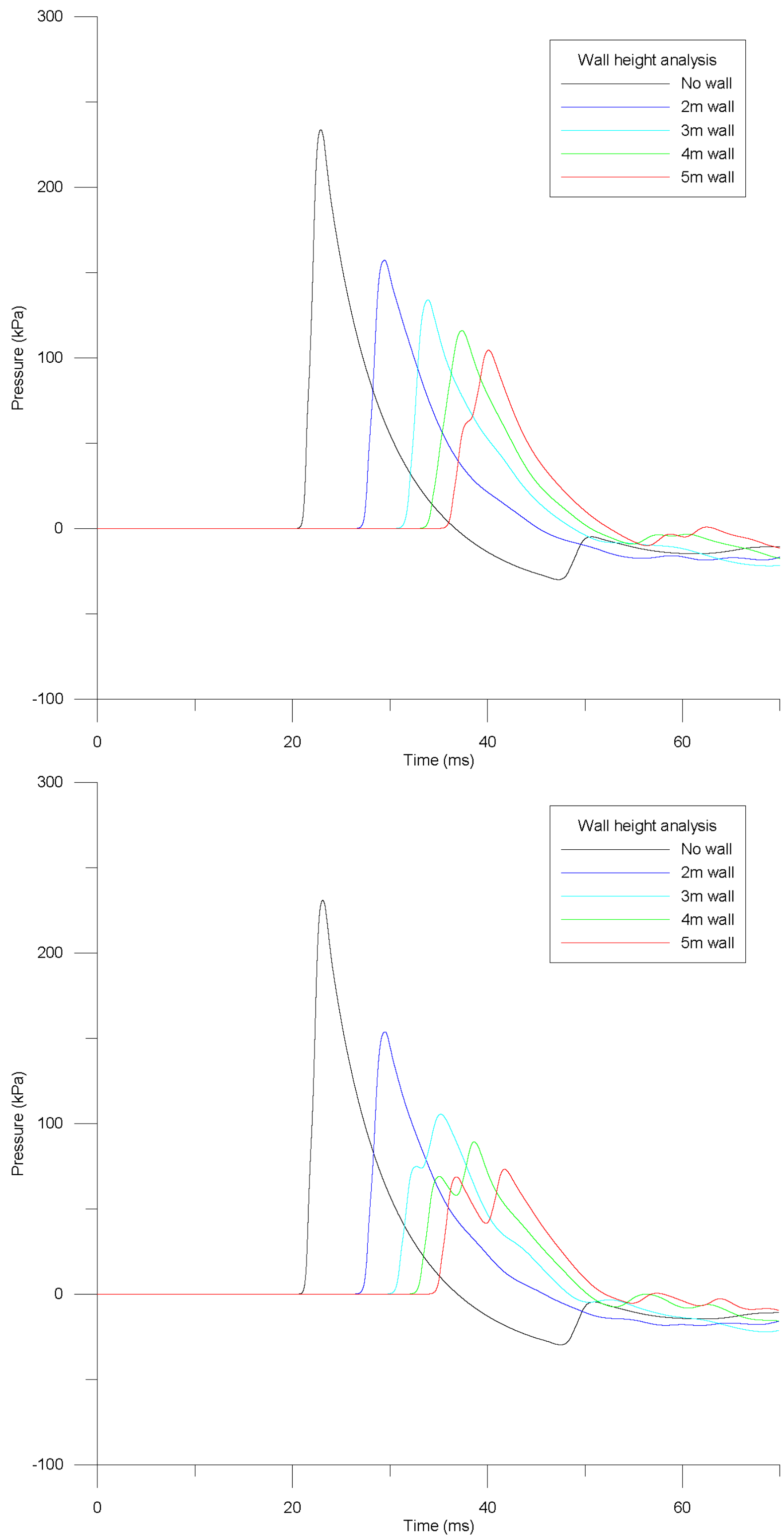
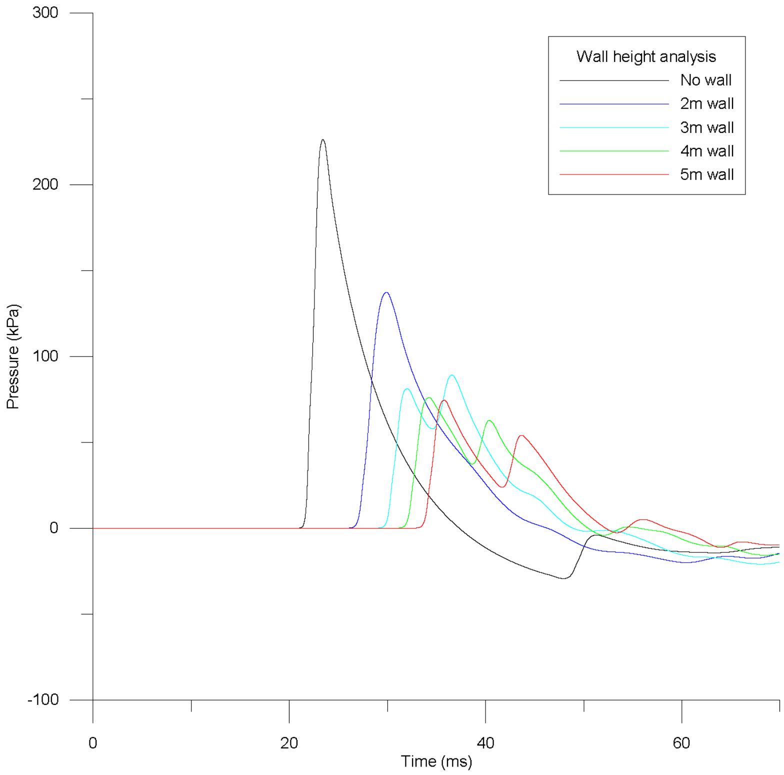


Figure A.25. Pressures on point 1(1m above the ground, top chart), and on point 2(2m above the ground, bottom chart) - 15m wall-building distance.



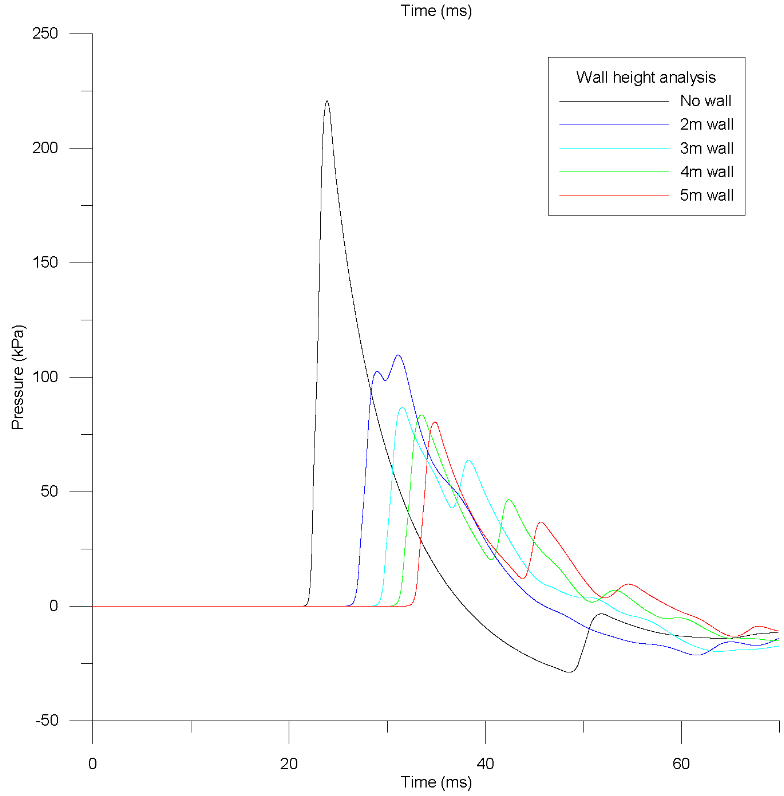


Figure A.26. Pressures on point 3(3m above the ground, top chart), and on point 4(4m above the ground, bottom chart) - 15m wall-building distance.

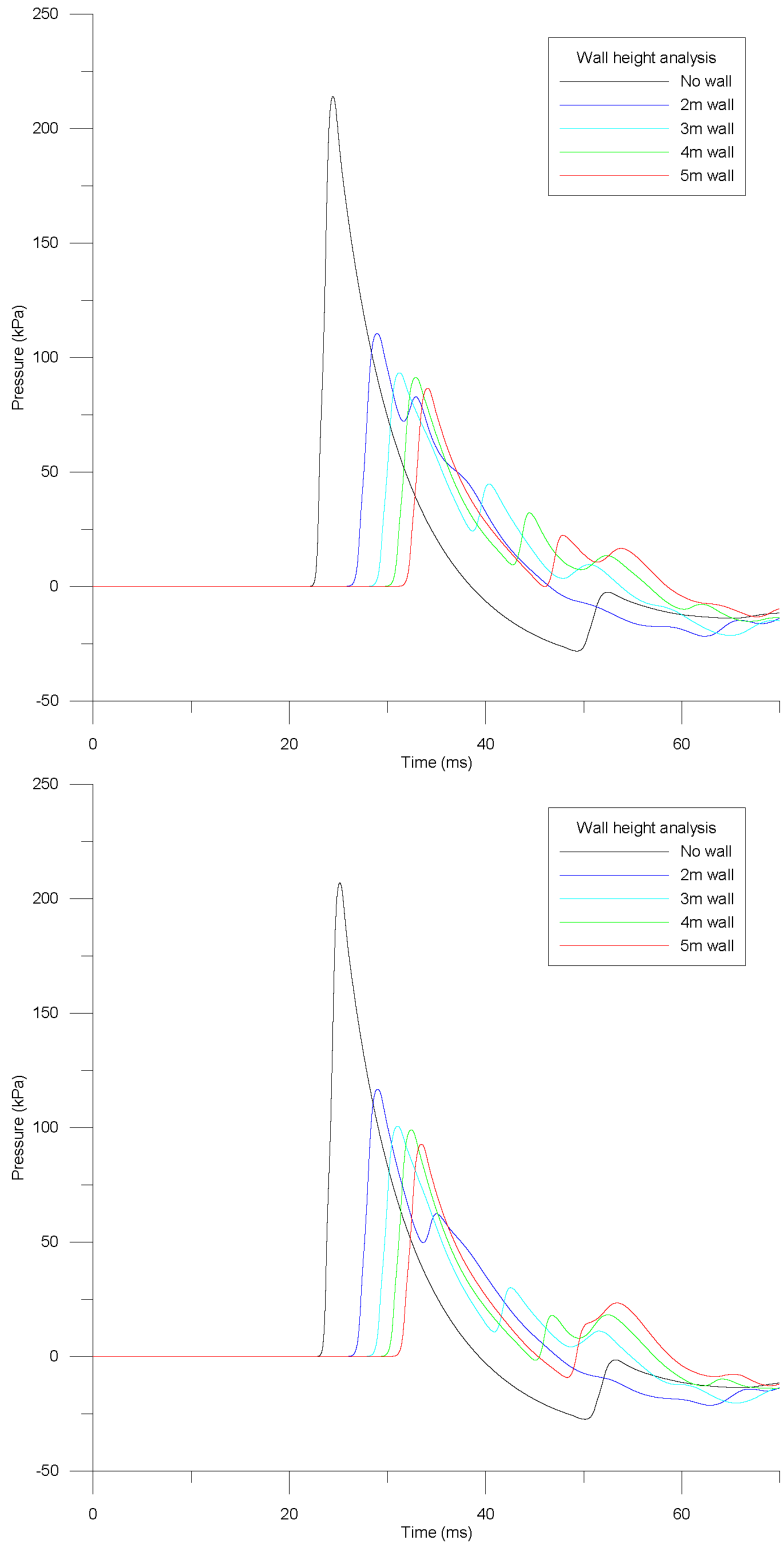


Figure A.27. Pressures on point 5(5m above the ground, top chart), and on point 6(6m above the ground, bottom chart) - 15m wall-building distance.

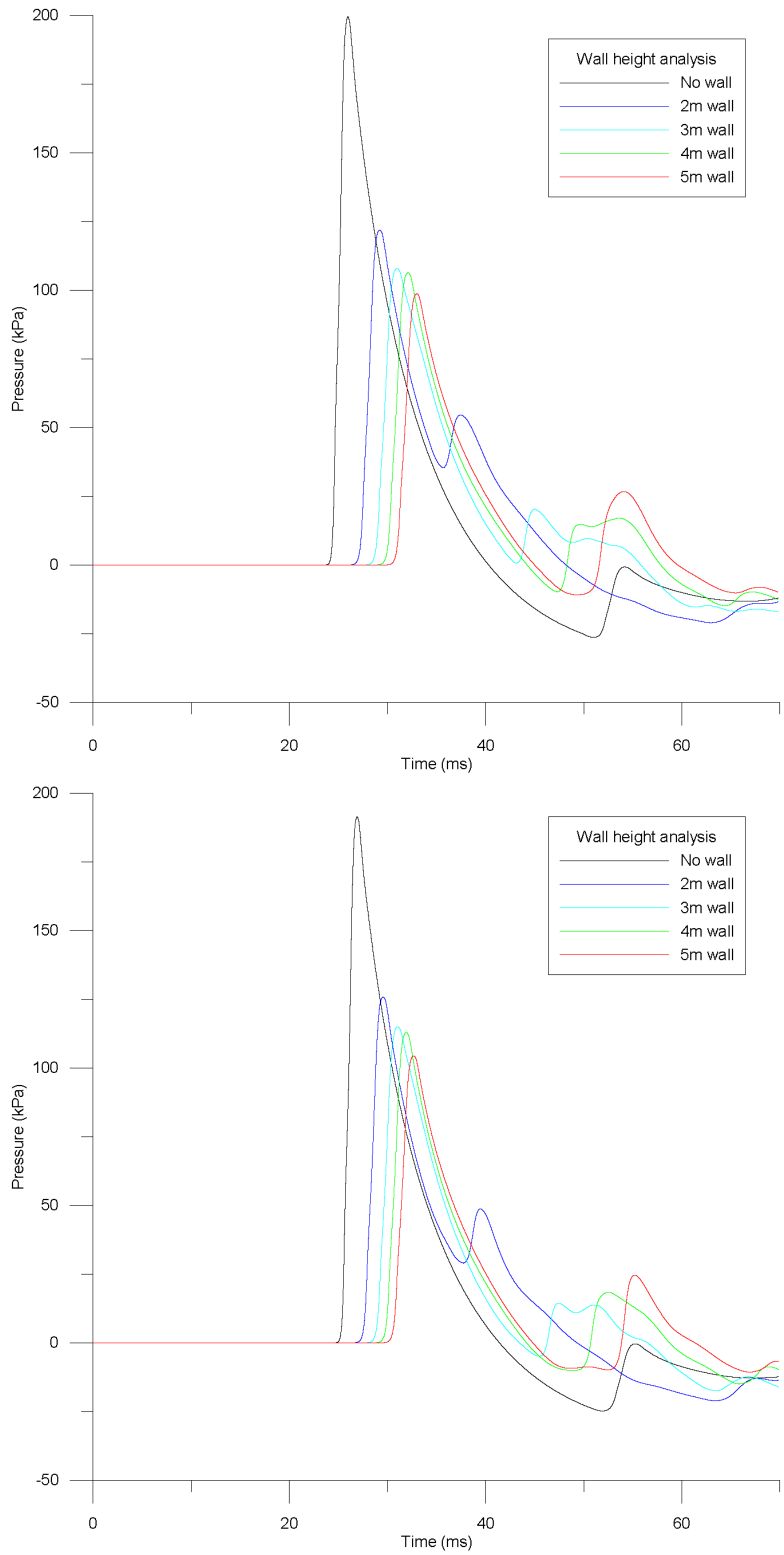


Figure A.28. Pressures on point 7(7m above the ground, top chart), and on point 8(8m above the ground, bottom chart) - 15m wall-building distance.

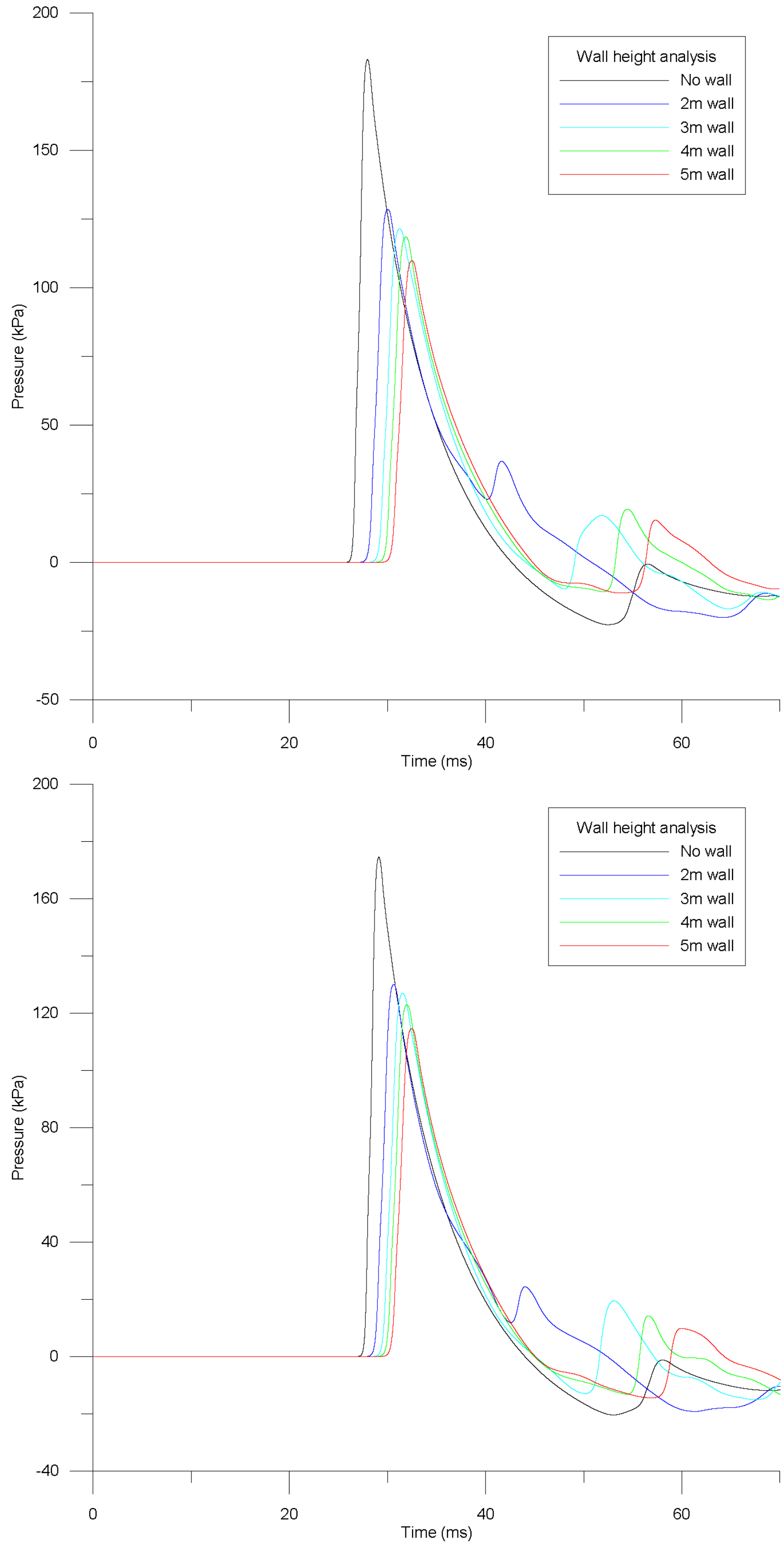


Figure A.29. Pressures on point 9(9m above the ground, top chart), and on point 10(10m above the ground, bottom chart) - 15m wall-building distance.

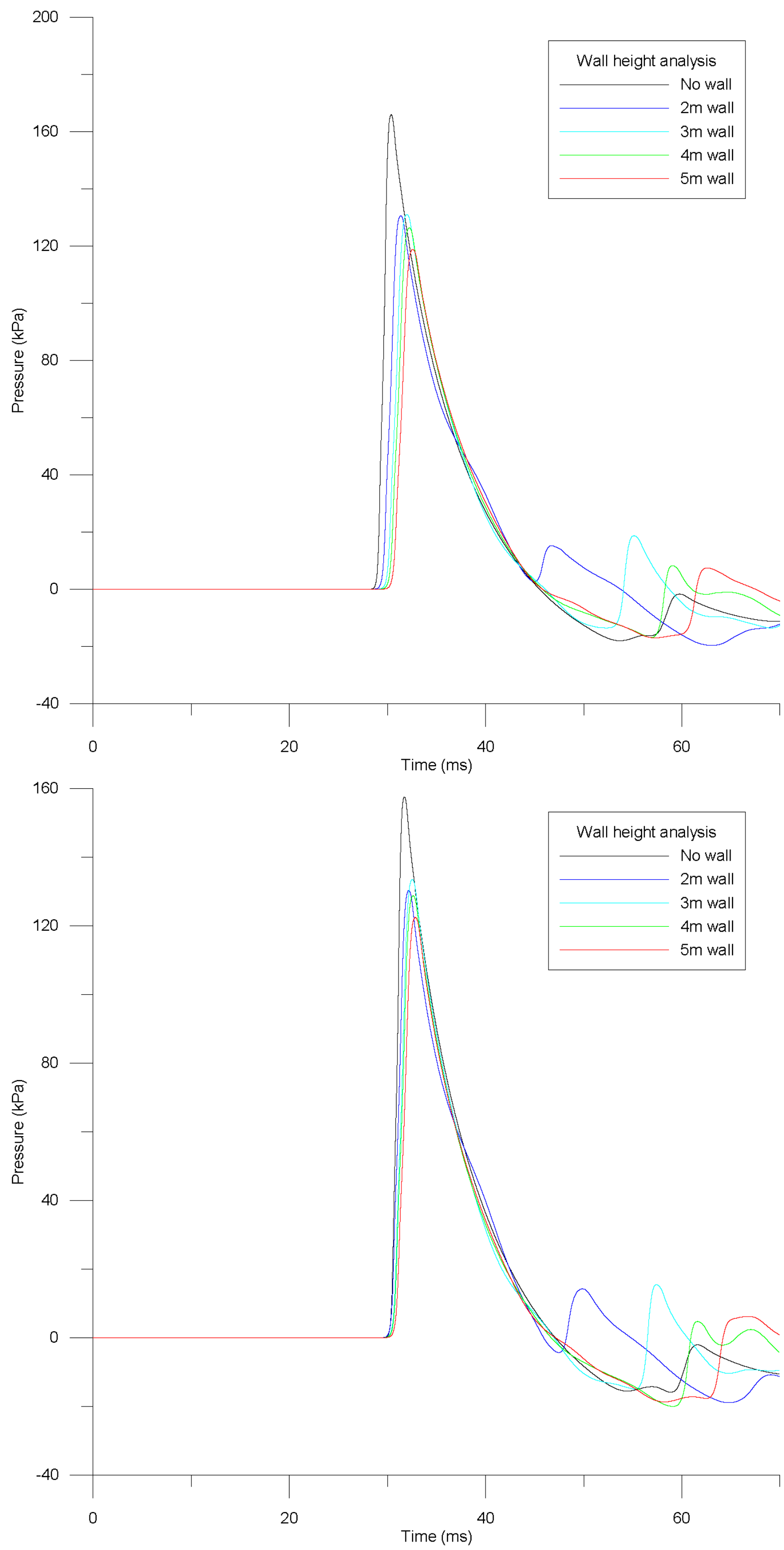
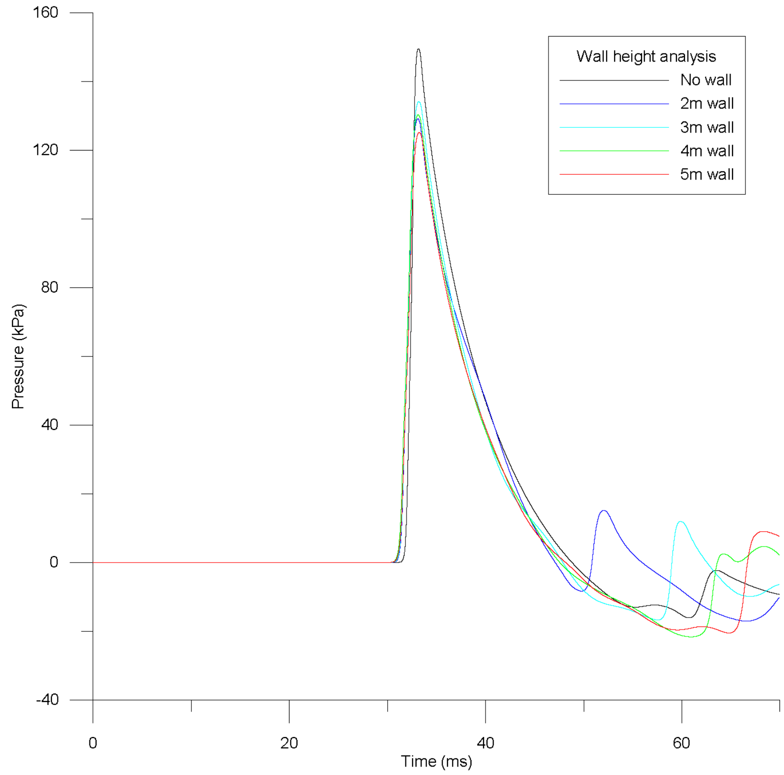


Figure A.30. Pressures on point 11(11m above the ground, top chart), and on point 12(12m above the ground, bottom chart) - 15m wall-building distance.



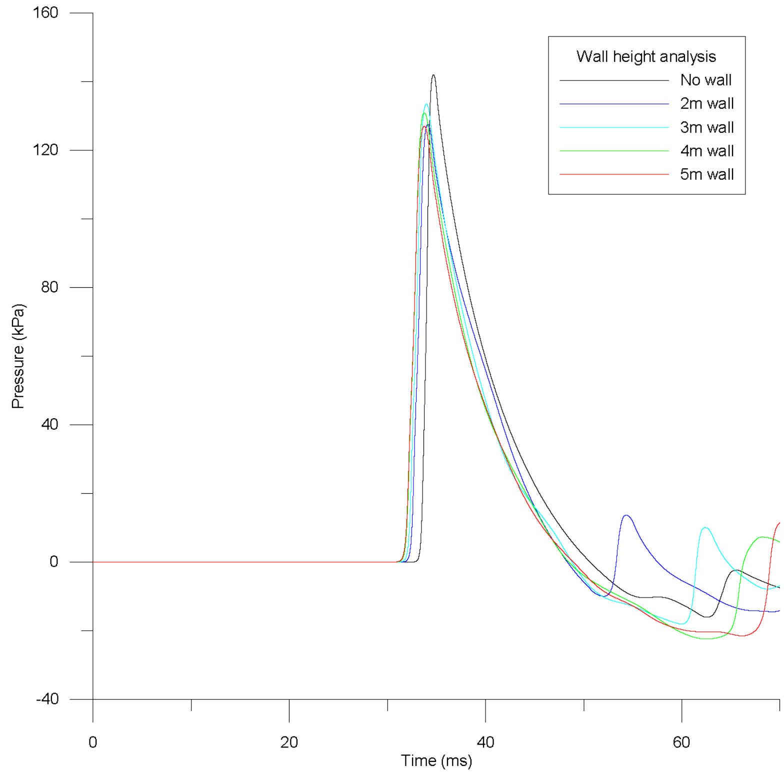


Figure A.31. Pressures on point 13(13m above the ground, top chart), and on point 14(14m above the ground, bottom chart) - 15m wall-building distance.

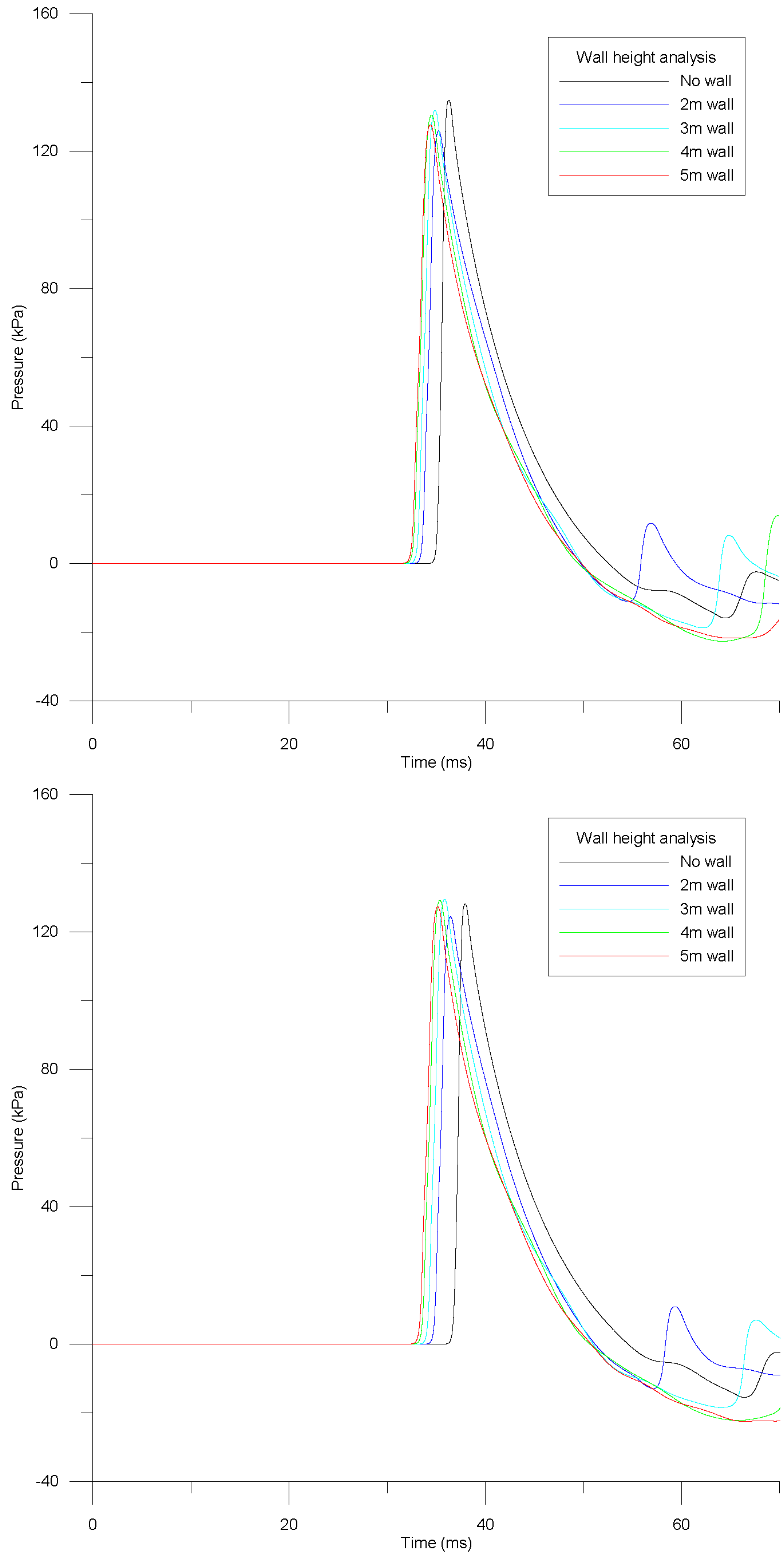


Figure A.32. Pressures on point 15(15m above the ground, top chart), and on point 16(16m above the ground, bottom chart) - 15m wall-building distance.

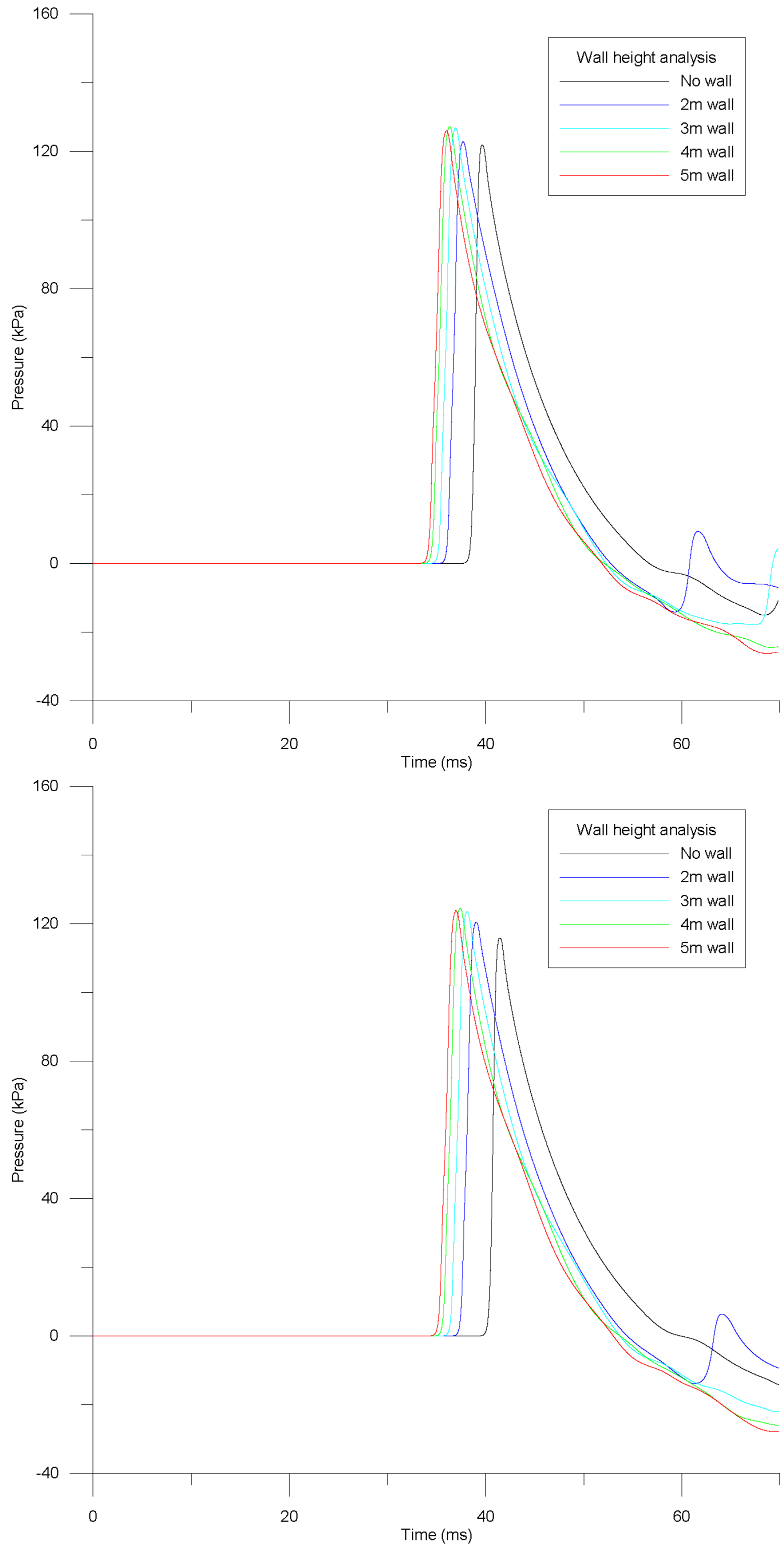


Figure A.33. Pressures on point 17(17m above the ground, top chart), and on point 18(18m above the ground, bottom chart) - 15m wall-building distance.

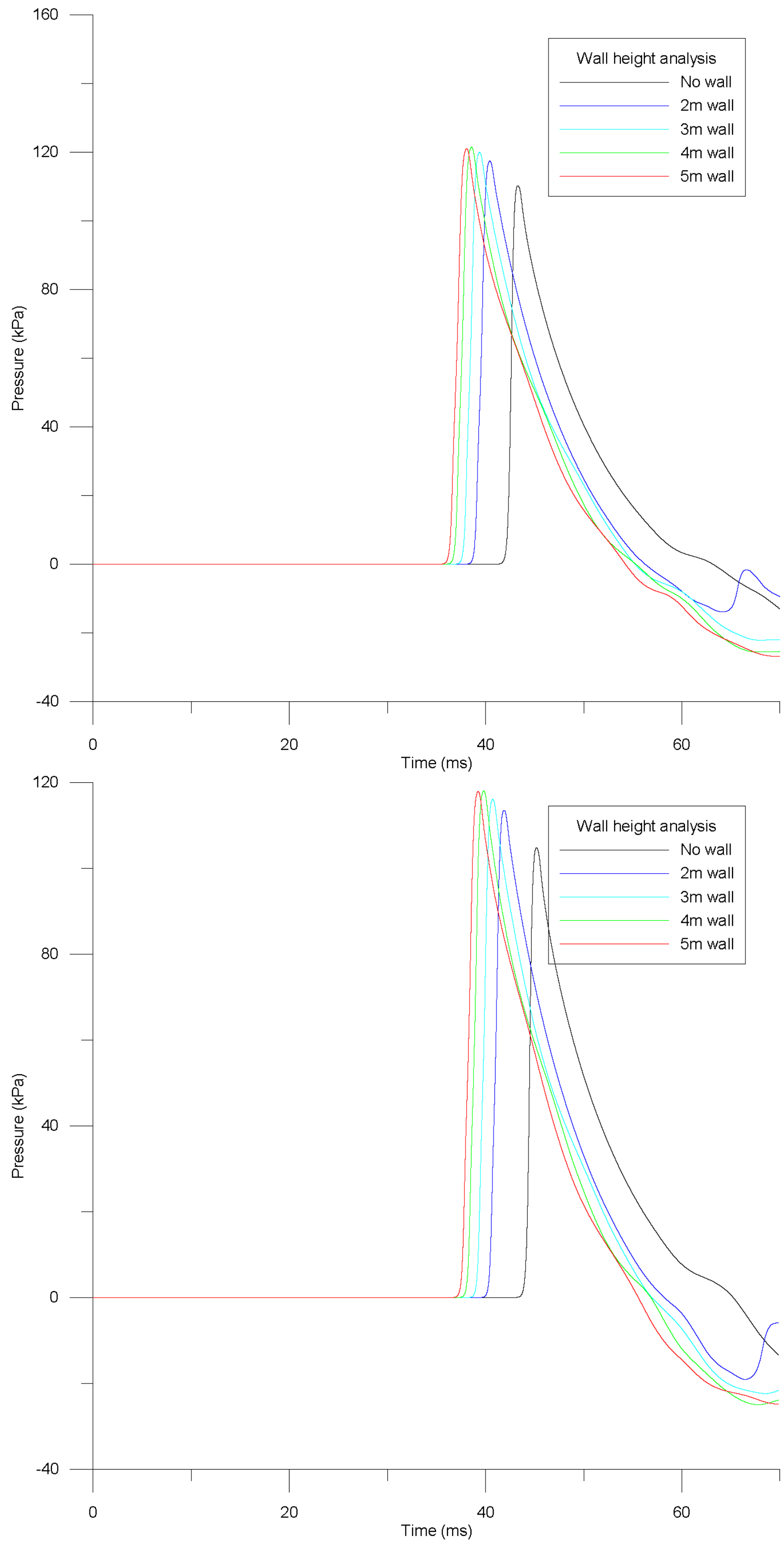


Figure A.34. Pressures on point 19(19m above the ground, top chart), and on point 20(20m above the ground, bottom chart) - 15m wall-building distance.

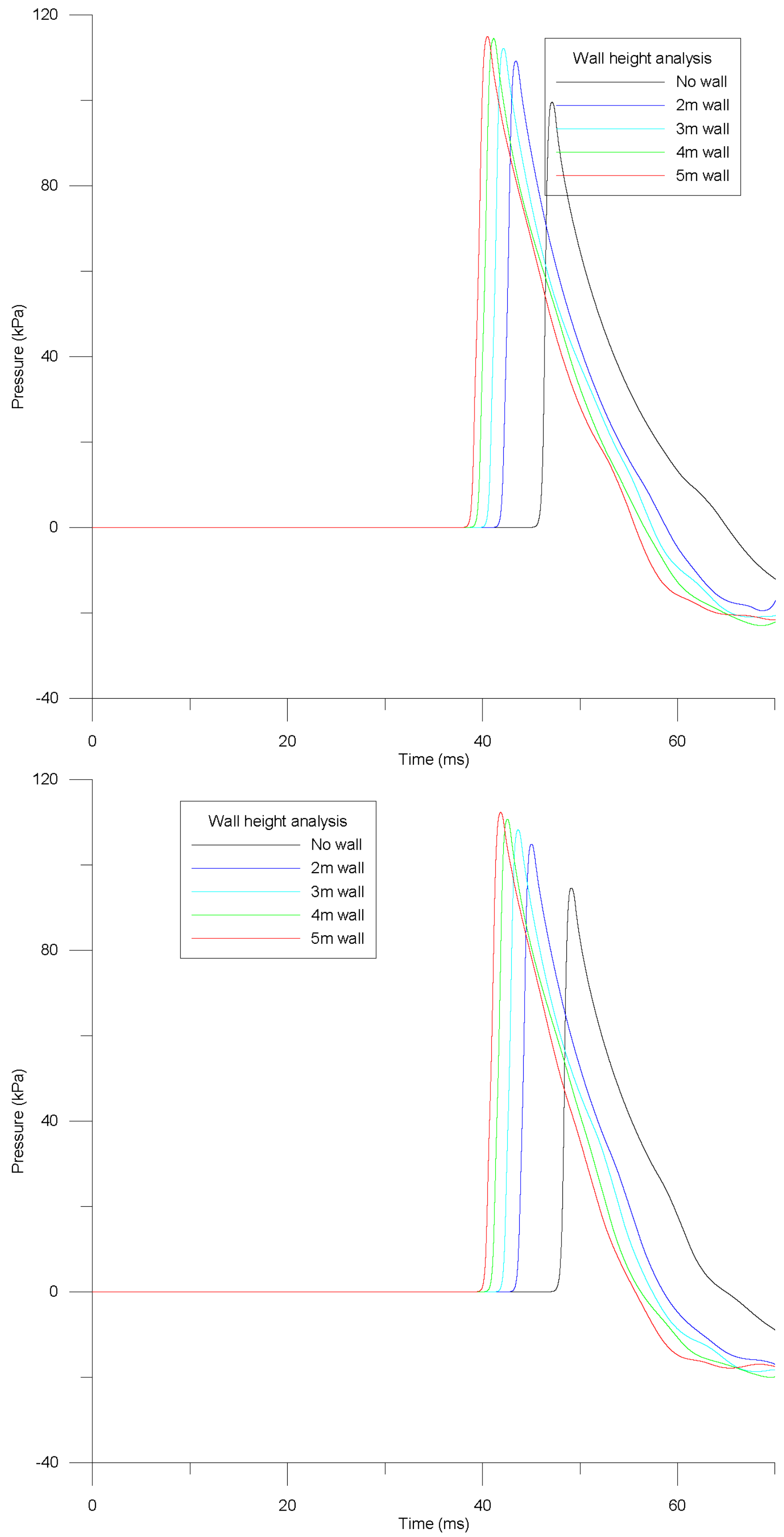


Figure A.35. Pressures on point 21(21m above the ground, top chart), and on point 22(22m above the ground, bottom chart) - 15m wall-building distance.

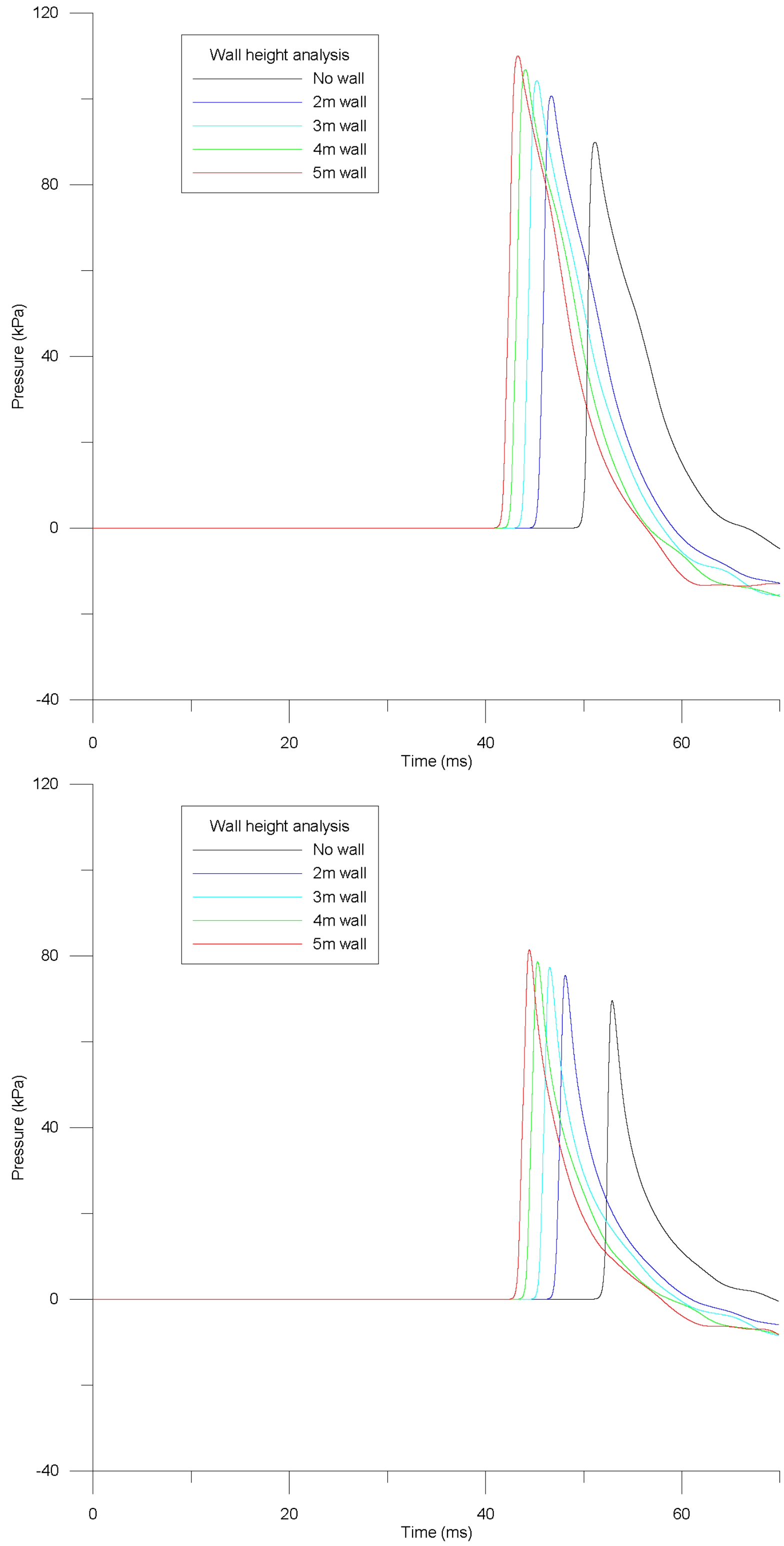
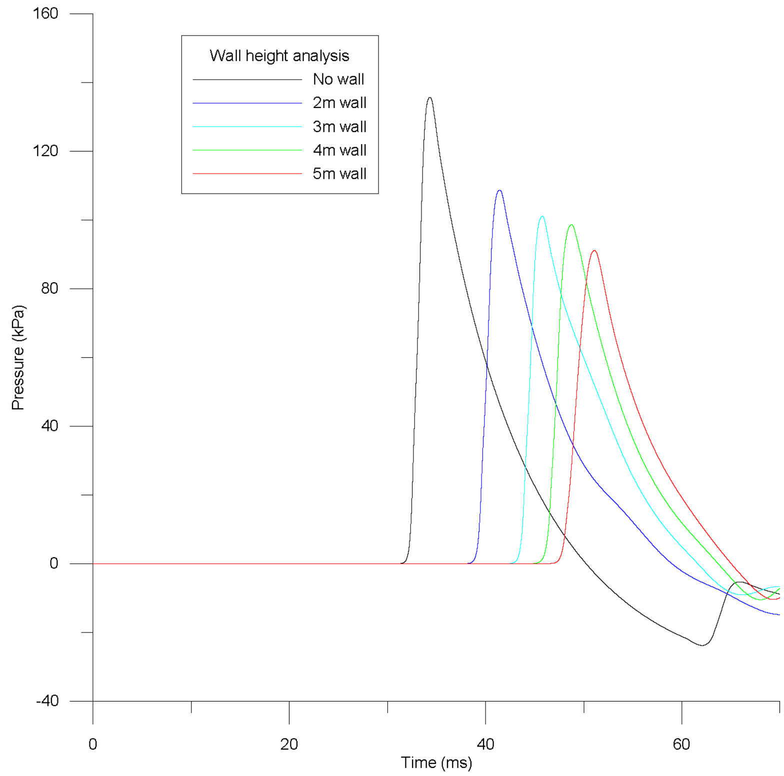


Figure A.36. Pressures on point 23(23m above the ground, top chart), and on point 24(24m above the ground, bottom chart) - 15m wall-building distance.



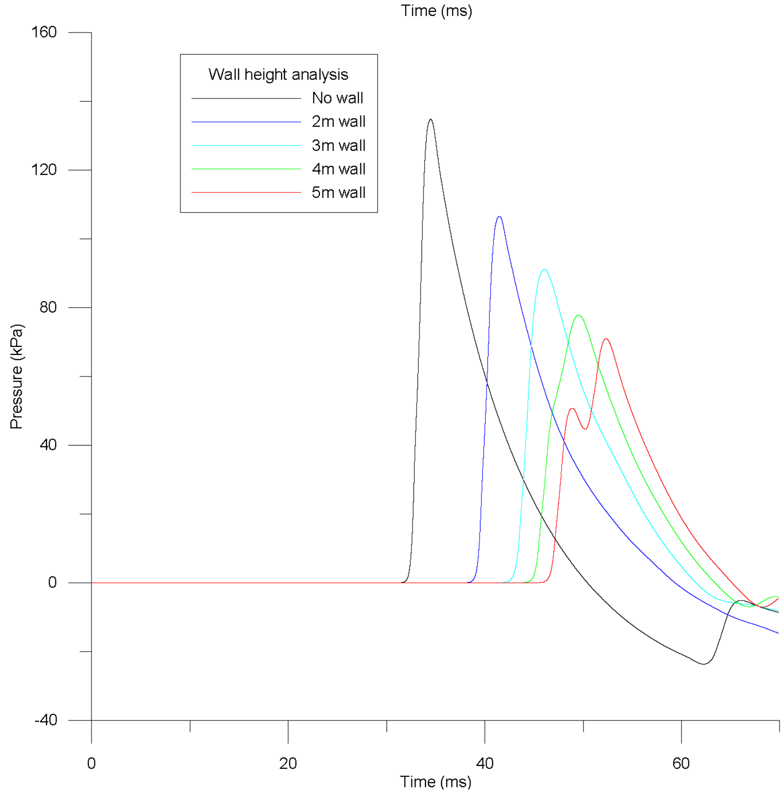


Figure A.37. Pressures on point 1(1m above the ground, top chart), and on point 2(2m above the ground, bottom chart) - 20m wall-building distance.

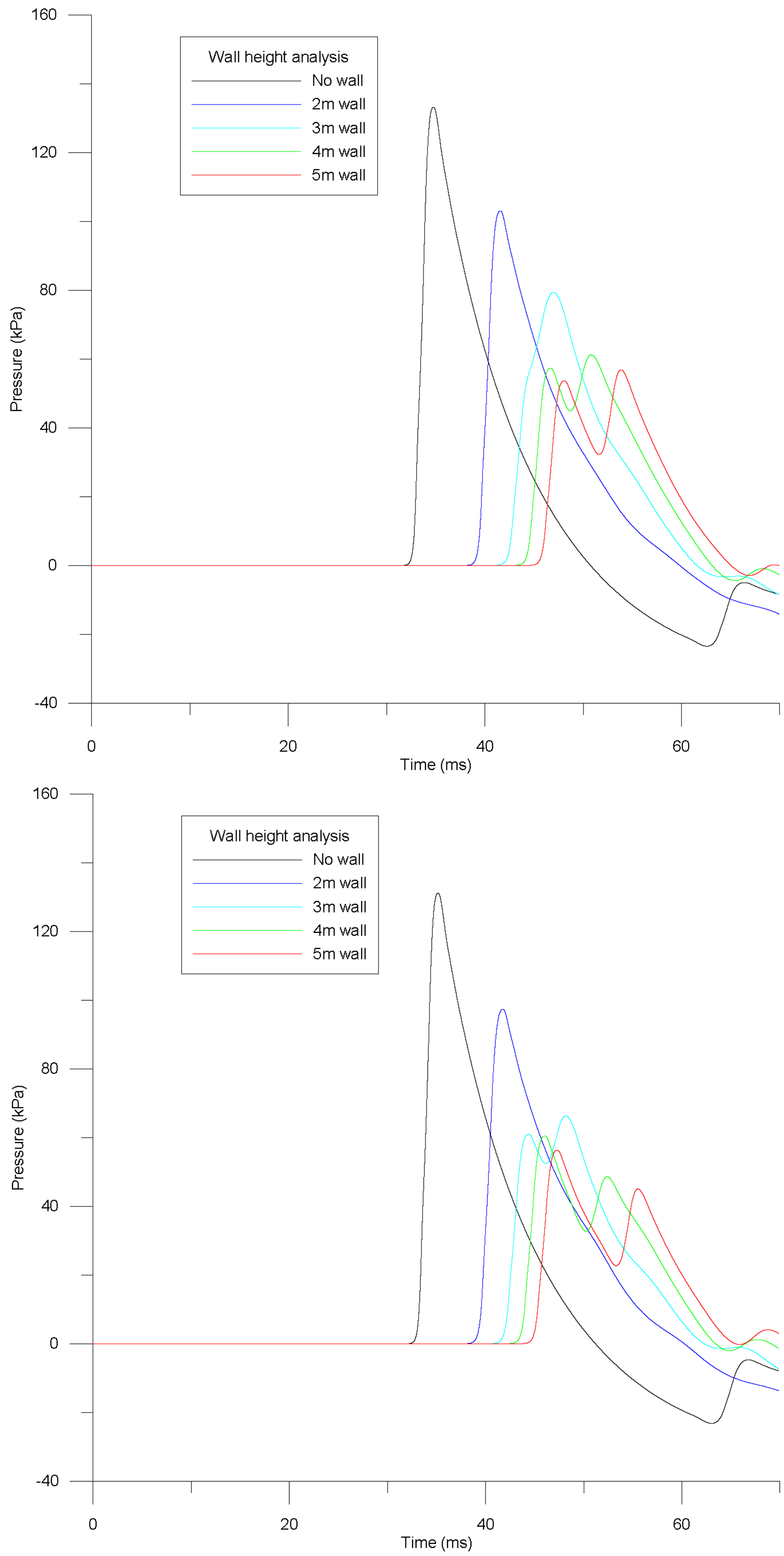


Figure A.38. Pressures on point 3(3m above the ground, top chart), and on point 4(4m above the ground, bottom chart) - 20m wall-building distance.

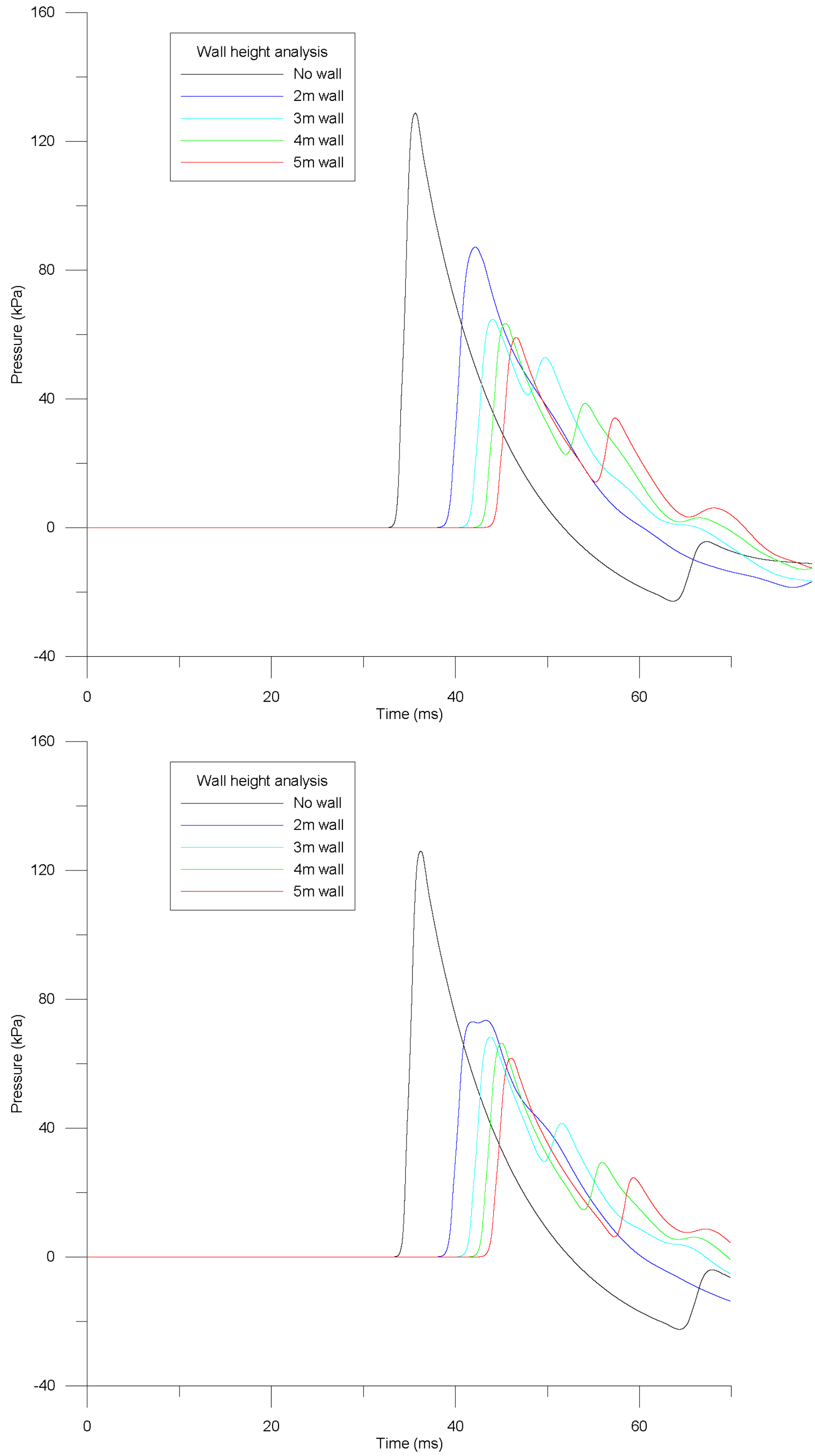


Figure A.39. Pressures on point 5(5m above the ground, top chart), and on point 6(6m above the ground, bottom chart) - 20m wall-building distance.

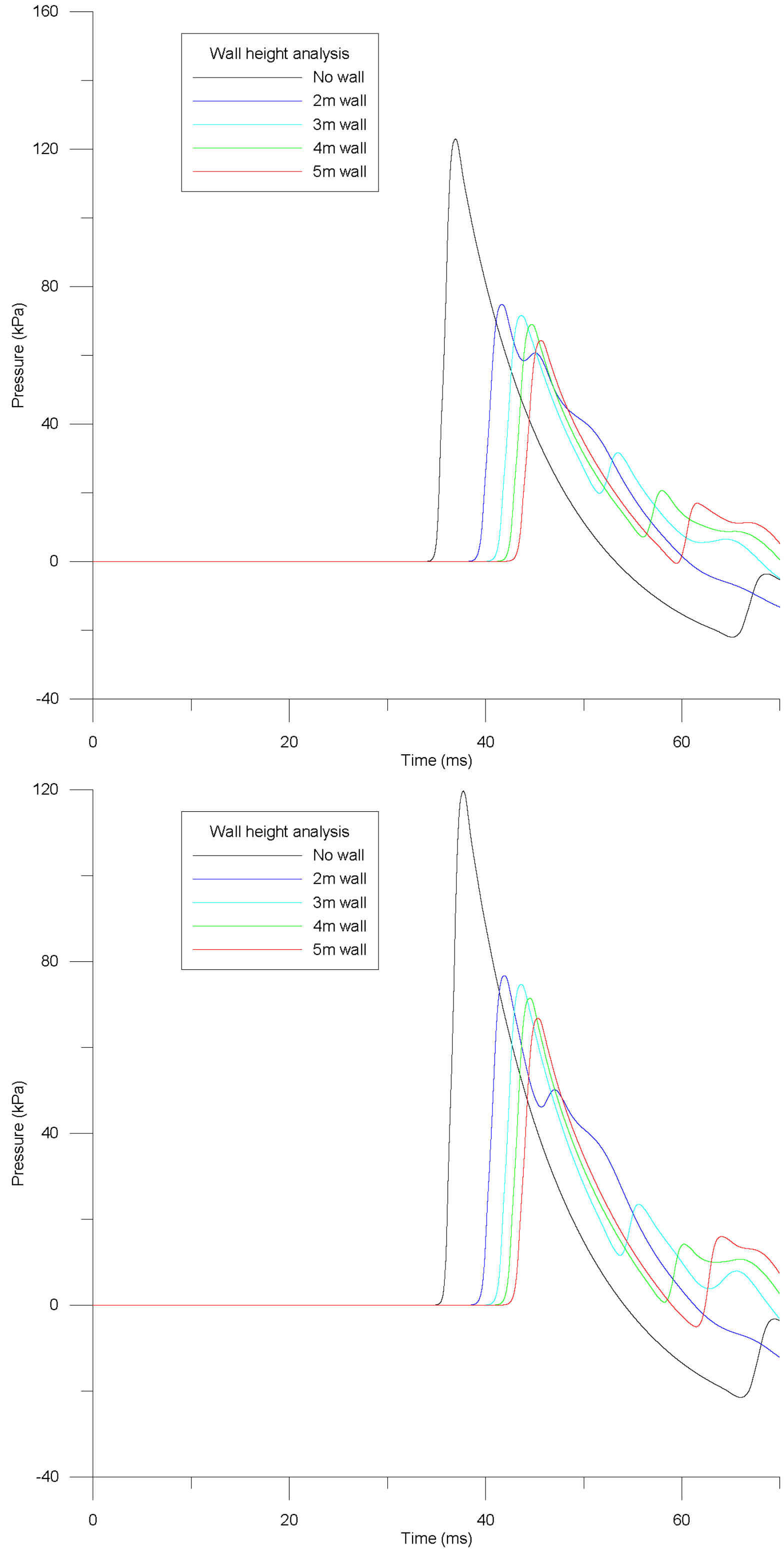


Figure A.40. Pressures on point 7(7m above the ground, top chart), and on point 8(8m above the ground, bottom chart) - 20m wall-building distance.

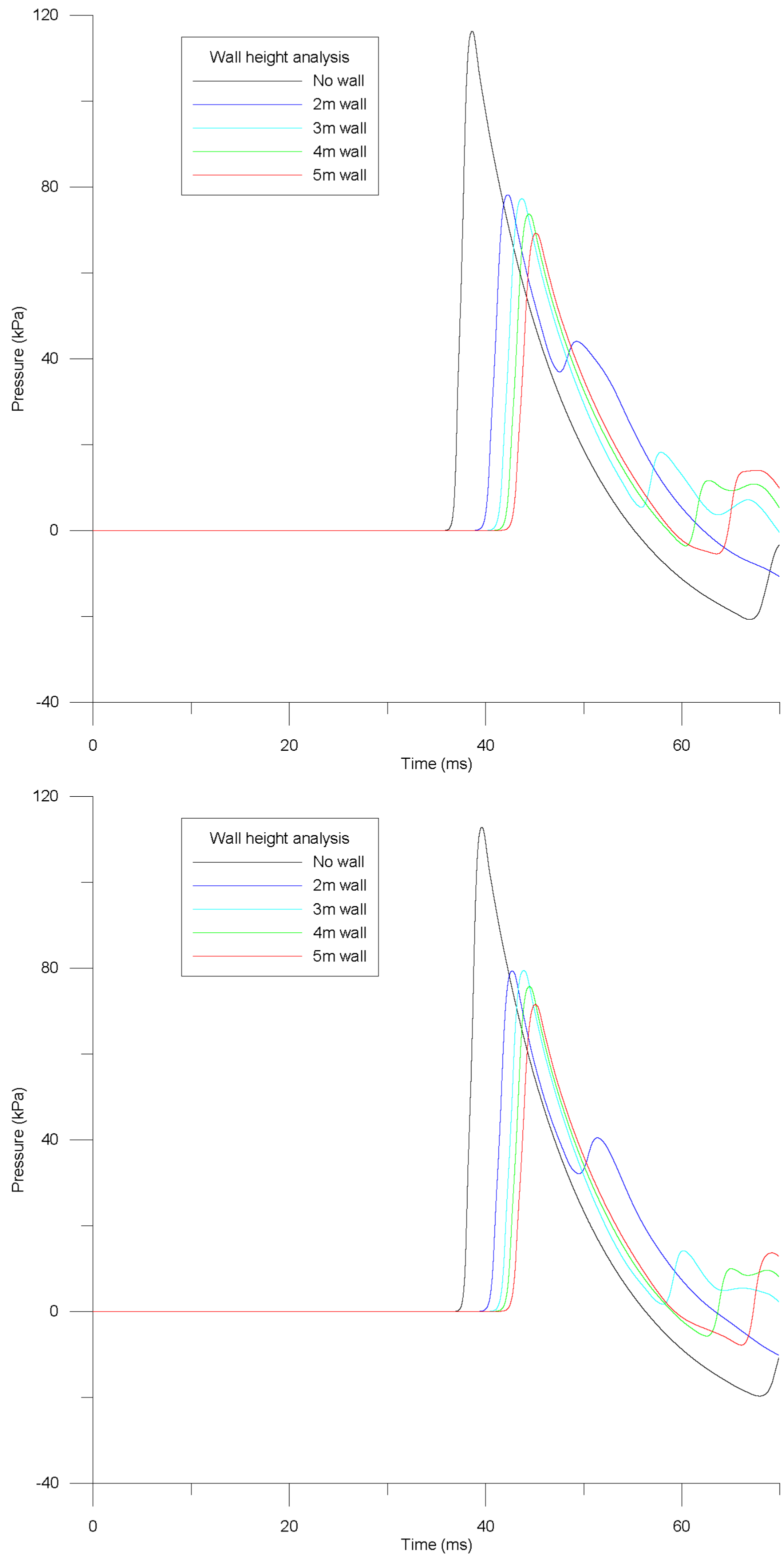


Figure A.41. Pressures on point 9(9m above the ground, top chart), and on point 10(10m above the ground, bottom chart) - 20m wall-building distance.

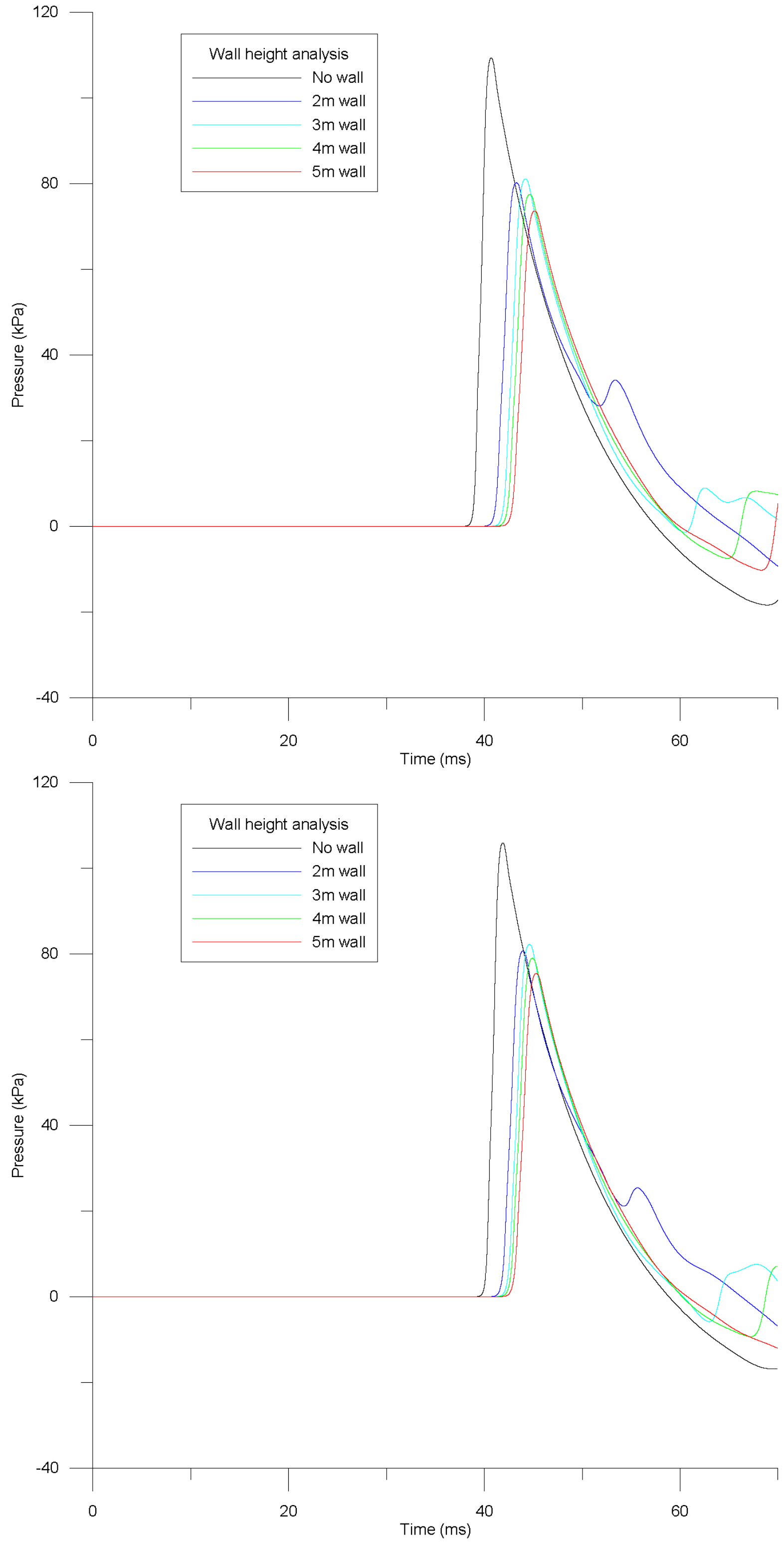
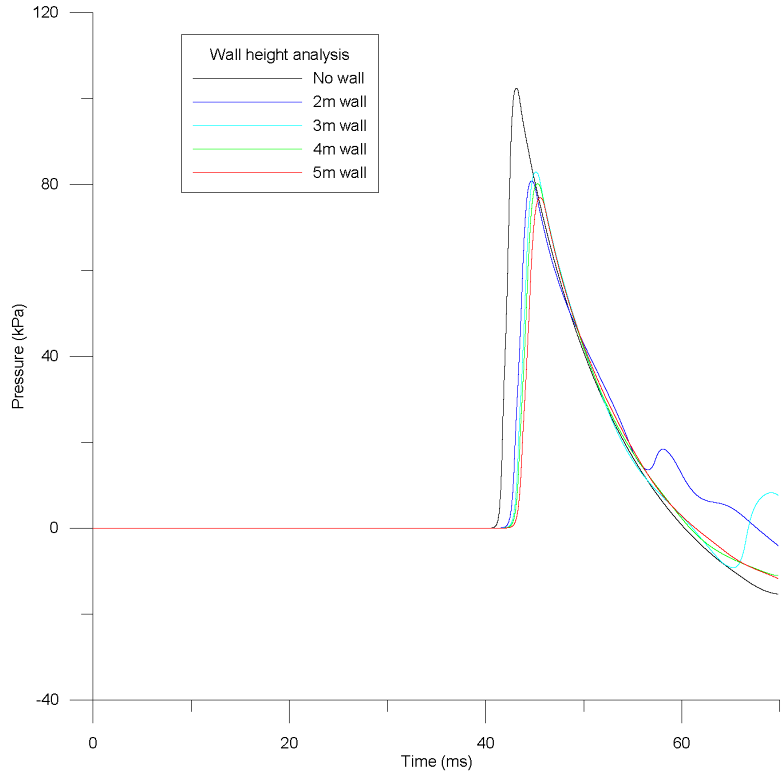


Figure A.42. Pressures on point 11(11m above the ground, top chart), and on point 12(12m above the ground, bottom chart) - 20m wall-building distance.



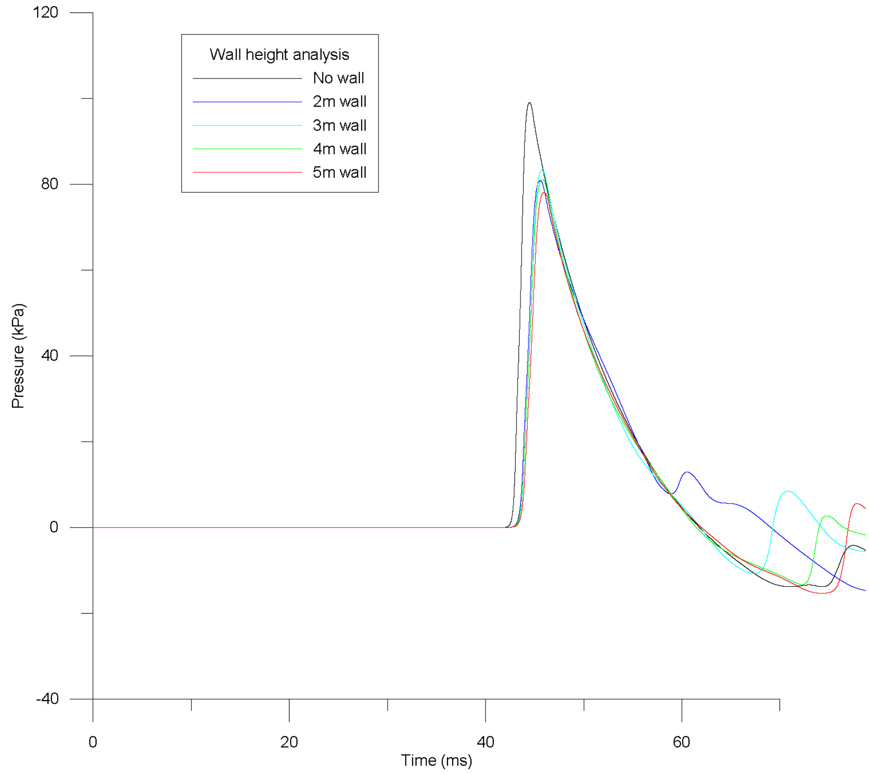


Figure A.43. Pressures on point 13(13m above the ground, top chart), and on point 14(14m above the ground, bottom chart) - 20m wall-building distance.

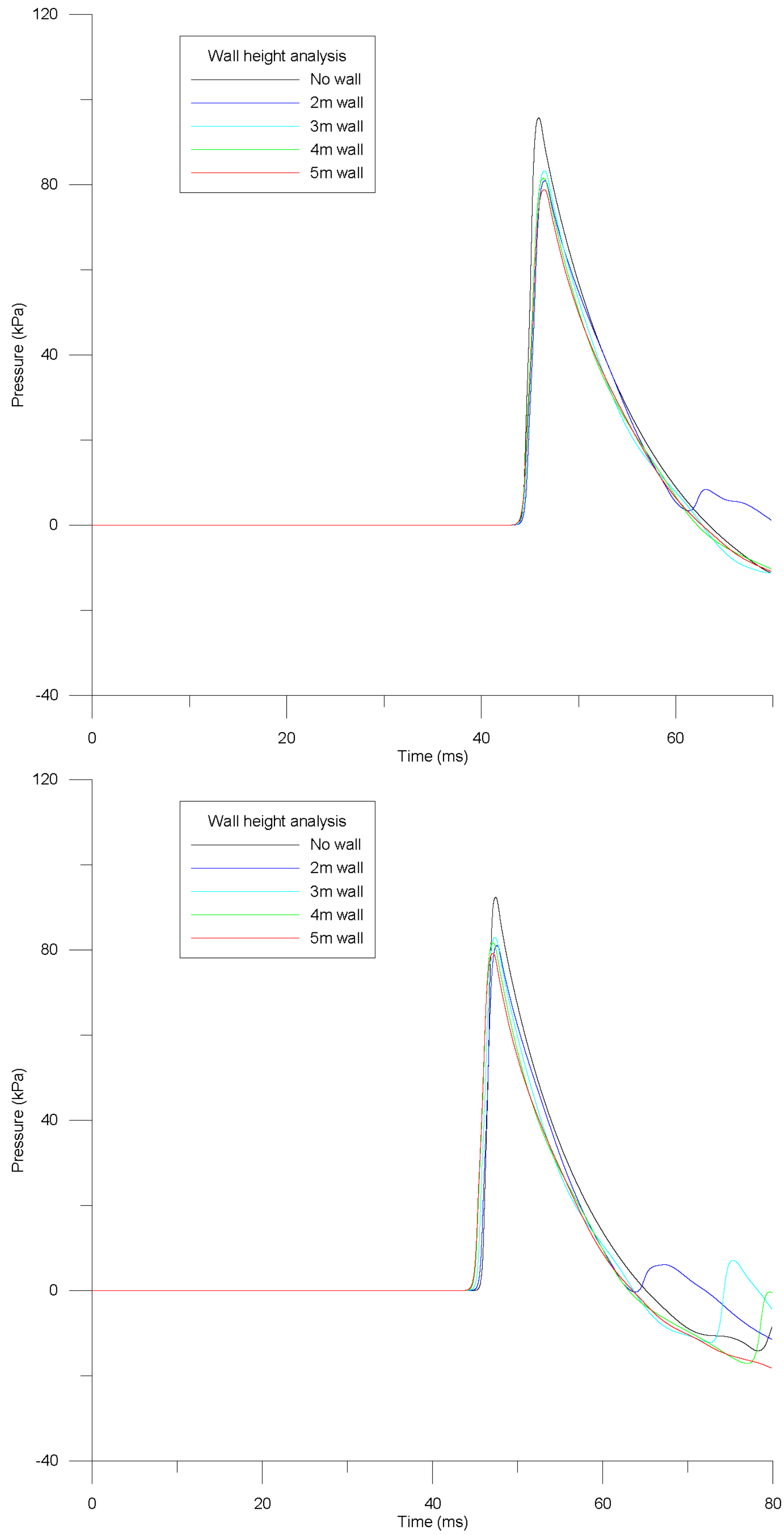


Figure A.44. Pressures on point 15(15m above the ground, top chart), and on point 16(16m above the ground, bottom chart) - 20m wall-building distance.

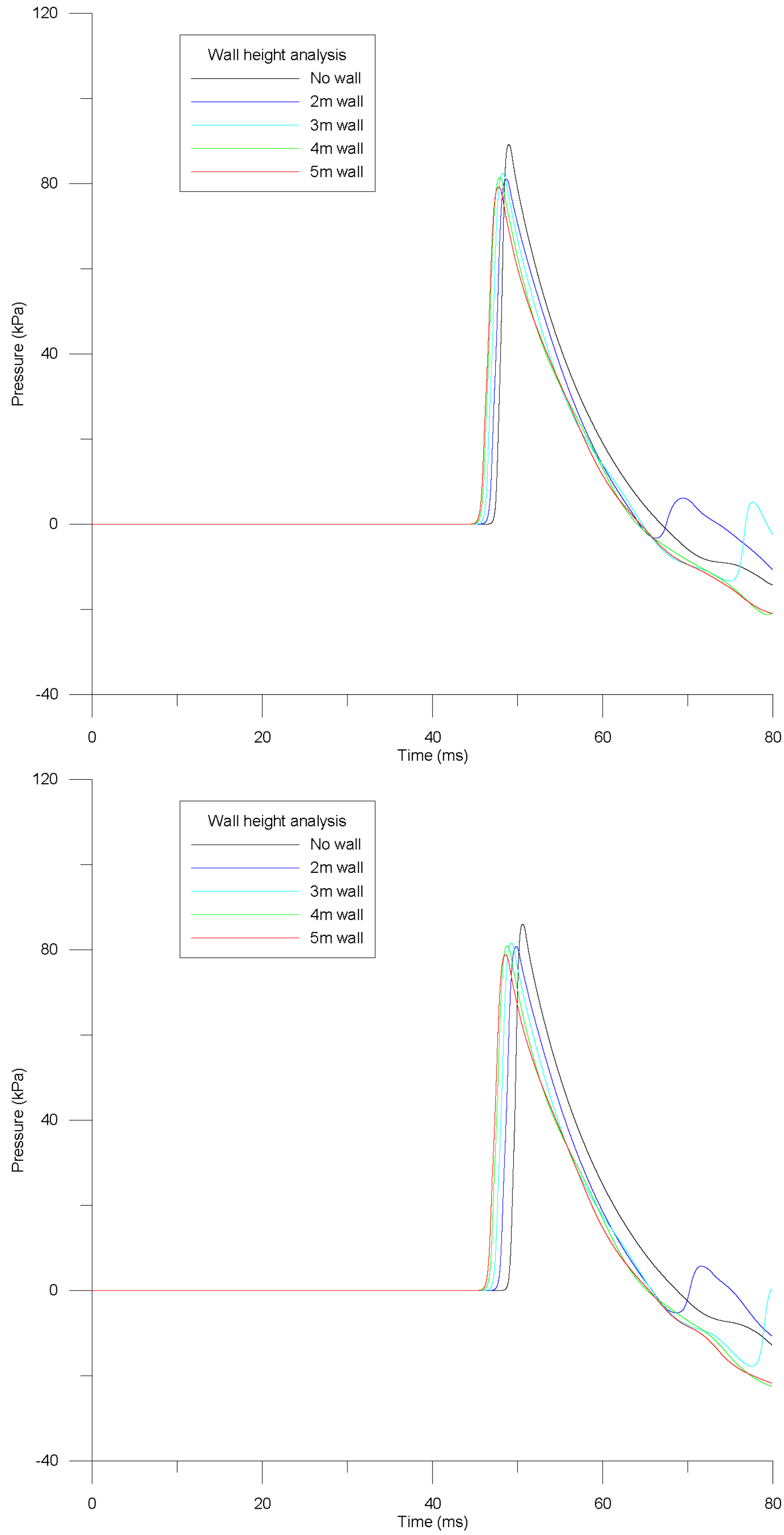


Figure A.45. Pressures on point 17(17m above the ground, top chart), and on point 18(18m above the ground, bottom chart) - 20m wall-building distance.

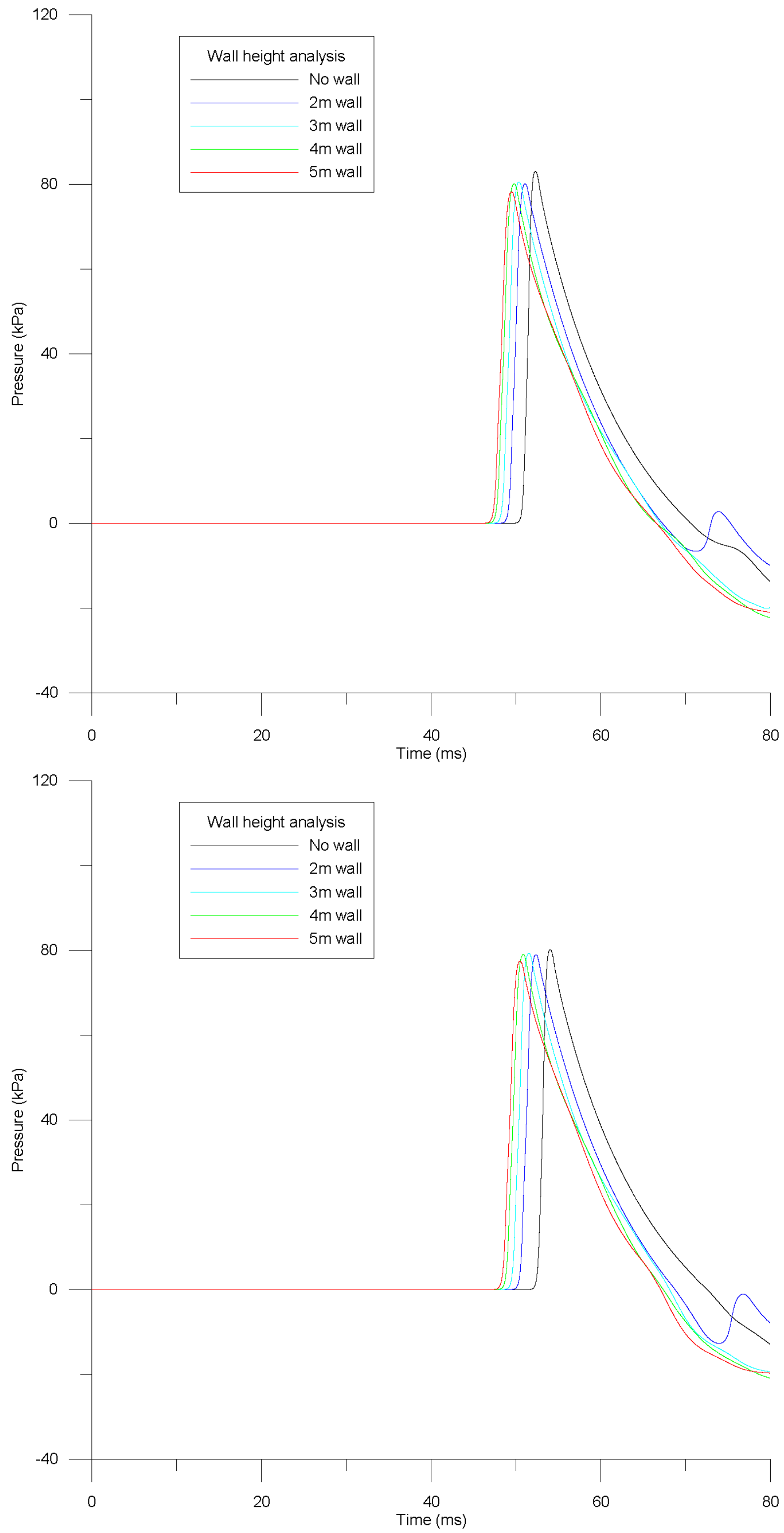


Figure A.46. Pressures on point 19(19m above the ground, top chart), and on point 20(20m above the ground, bottom chart) - 20m wall-building distance.

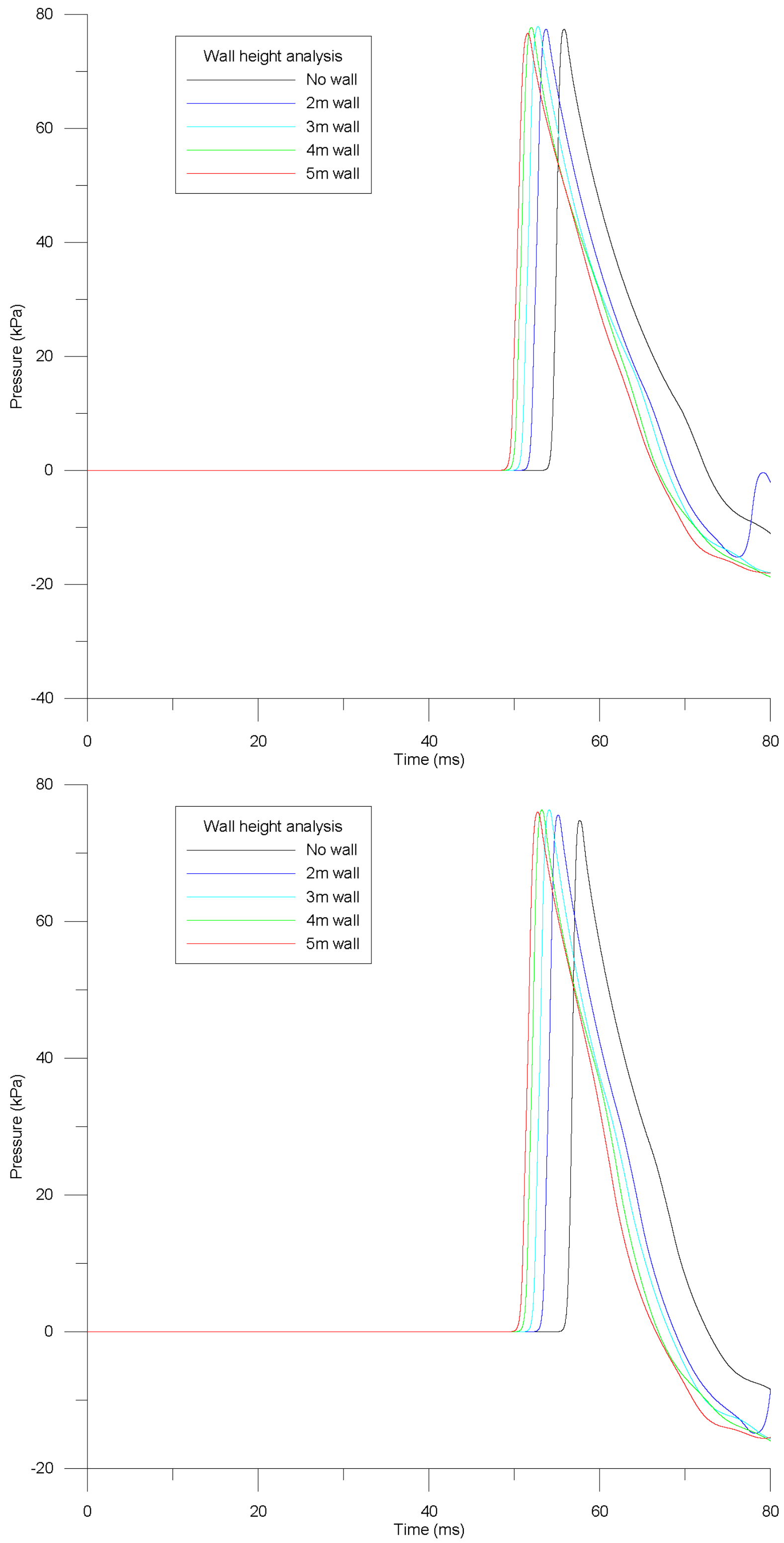


Figure A.47. Pressures on point 21(21m above the ground, top chart), and on point 22(22m above the ground, bottom chart) - 20m wall-building distance.

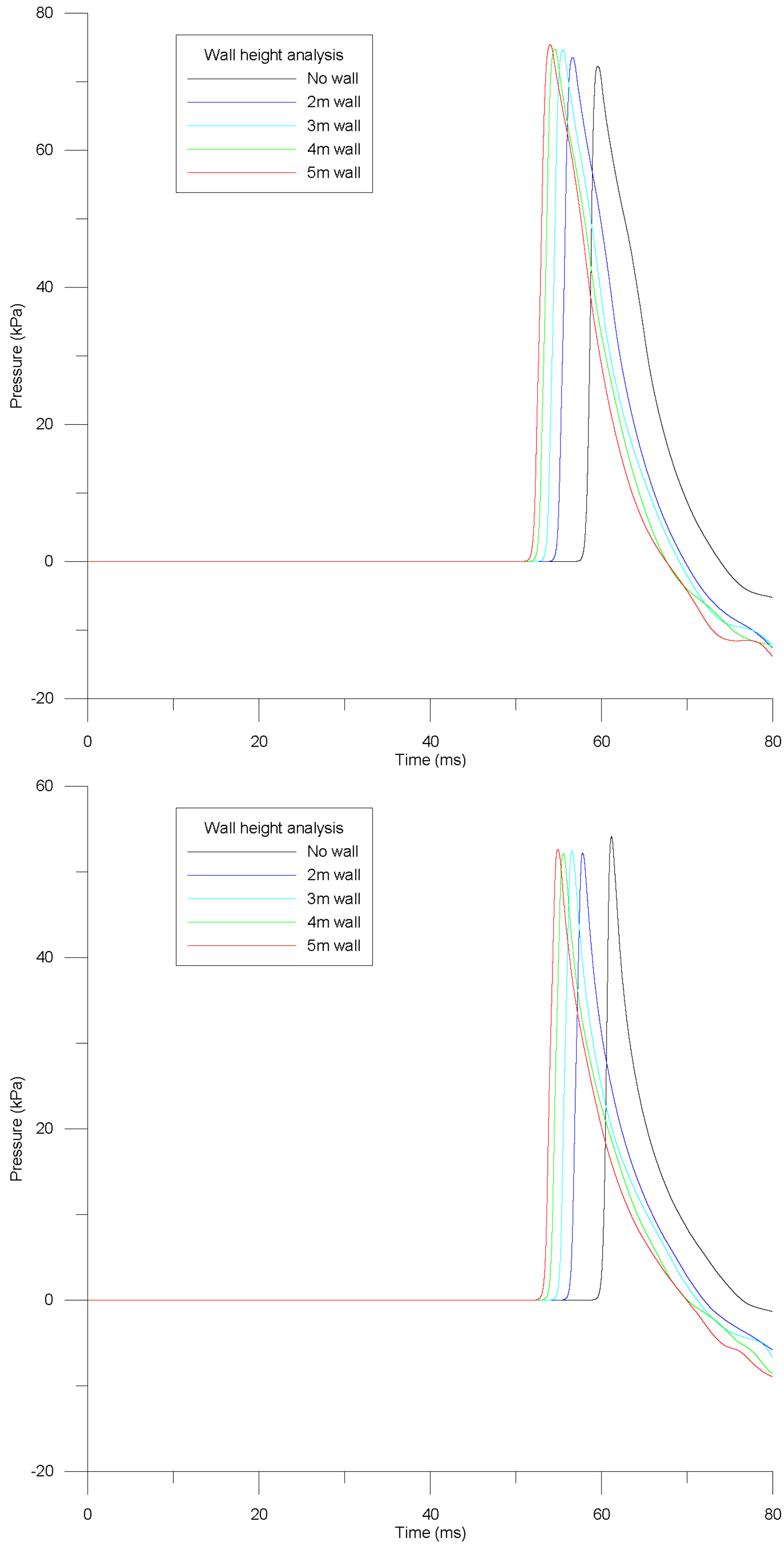


Figure A.48. Pressures on point 23(23m above the ground, top chart), and on point 24(24m above the ground, bottom chart) - 20m wall-building distance.

APPENDIX B: TABLES FOR REDUCTIONS IN IMPULSE WITH EACH 5M INCREASE

The reductions in the impulse are given for each extra 5m distance provided. Each table represents a different wall height.

Table B.1. Percent reduction of impulses for different distances (No wall analyses).

	% Reduction		
Height	5m -> 10m	10m -> 15m	15m -> 20m
1 m	59,8	38,6	26,9
2 m	57,5	38,5	26,6
3 m	54,5	38,1	26,1
4 m	52,6	37,3	25,5
5 m	51,8	36,3	24,7
6 m	50,7	35,2	23,8
7 m	49,2	34,3	22,7
8 m	48,3	33,6	21,7
9 m	48,3	33,3	20,4
10 m	48,5	33,3	19,3
11 m	48,9	33,8	18,2
12 m	49,2	34,6	17,3
13 m	49,1	35,7	16,3
14 m	48,8	36,7	15,4
15 m	48,2	37,4	14,7
16 m	48,9	37,9	14,0
17 m	50,0	38,0	13,4
18 m	50,7	37,7	12,9
19 m	50,5	37,1	13,1
20 m	49,4	36,6	13,4
21 m	48,1	36,8	13,3
22 m	47,5	38,1	13,3
23 m	48,2	38,9	12,9
24 m	18,9	11,1	7,5

Table B.2. Percent reduction of impulses for different distances (2m wall analyses).

	% Reduction		
Height	5m -> 10m	10m -> 15m	15m -> 20m
1 m	46,7	33,3	21,6
2 m	47,4	30,8	21,1
3 m	51,9	29,7	20,1
4 m	54,9	30,8	19,0
5 m	56,5	32,2	18,7
6 m	56,9	33,1	18,9
7 m	56,2	34,0	19,1
8 m	54,6	34,9	19,1
9 m	52,2	36,8	19,1
10 m	50,4	38,9	19,1
11 m	49,8	40,2	19,2
12 m	49,3	40,8	19,1
13 m	48,2	40,8	18,9
14 m	46,9	40,3	18,6
15 m	45,7	38,5	20,0
16 m	45,5	36,7	21,1
17 m	46,6	35,4	22,0
18 m	47,7	34,5	22,6
19 m	48,7	32,8	21,9
20 m	48,9	31,2	20,9
21 m	48,5	29,0	20,9
22 m	49,3	28,0	20,9
23 m	49,3	28,0	20,2
24 m	18,2	-10,9	10,9

Table B.3. Percent reduction of impulses for different distances (3m wall analyses).

	% Reduction		
Height	5m -> 10m	10m -> 15m	15m -> 20m
1 m	44,6	28,2	17,5
2 m	43,9	27,7	15,6
3 m	46,1	28,6	14,4
4 m	51,8	30,0	14,5
5 m	56,8	31,8	15,4
6 m	58,9	35,6	15,9
7 m	58,4	39,2	16,2
8 m	57,0	41,6	16,5
9 m	55,4	43,2	17,2
10 m	53,7	44,2	18,1
11 m	51,8	43,0	21,4
12 m	49,6	40,7	24,9
13 m	47,8	37,8	27,7
14 m	46,8	34,7	27,5
15 m	46,3	32,9	26,9
16 m	47,3	31,5	26,3
17 m	48,7	29,9	25,6
18 m	49,5	28,6	24,8
19 m	49,6	27,4	24,0
20 m	48,9	26,4	23,2
21 m	47,7	25,7	23,5
22 m	47,8	25,6	23,6
23 m	48,7	25,4	22,8
24 m	29,2	-31,6	13,1

Table B.4. Percent reduction of impulses for different distances (4m wall analyses).

Height	% Reduction		
	5m -> 10m	10m -> 15m	15m -> 20m
1 m	46,9	28,1	13,6
2 m	46,5	27,4	12,3
3 m	48,6	29,4	10,9
4 m	50,3	31,4	12,4
5 m	52,5	34,5	13,5
6 m	55,3	38,1	14,3
7 m	56,7	41,0	14,6
8 m	56,3	44,3	14,3
9 m	54,6	47,0	14,5
10 m	52,9	45,5	20,3
11 m	50,6	43,7	25,8
12 m	48,3	41,4	27,8
13 m	47,3	38,4	27,9
14 m	46,0	36,2	27,8
15 m	44,6	35,2	27,7
16 m	44,0	34,0	27,1
17 m	43,4	32,7	26,6
18 m	43,7	31,1	26,1
19 m	43,7	29,6	25,4
20 m	44,2	28,2	24,8
21 m	44,4	27,5	24,8
22 m	44,8	27,7	24,7
23 m	46,4	27,4	23,9
24 m	32,4	-30,0	14,3

Table B.5. Percent reduction of impulses for different distances (5m wall analyses).

Height	% Reduction		
	5m -> 10m	10m -> 15m	15m -> 20m
1 m	54,9	25,9	11,2
2 m	54,2	27,2	9,3
3 m	52,7	30,4	9,5
4 m	51,8	33,2	10,1
5 m	52,6	36,7	11,2
6 m	53,6	39,5	12,5
7 m	54,4	43,1	12,5
8 m	55,5	47,2	11,6
9 m	55,4	47,1	16,4
10 m	53,9	45,2	23,1
11 m	52,9	42,7	26,6
12 m	52,1	39,6	27,3
13 m	49,8	37,7	27,8
14 m	46,2	37,3	28,0
15 m	43,0	36,5	28,0
16 m	40,3	35,4	27,8
17 m	40,4	34,1	27,5
18 m	41,8	32,6	26,9
19 m	43,3	30,9	26,3
20 m	44,1	29,3	25,7
21 m	44,1	28,6	26,1
22 m	44,1	29,0	26,0
23 m	45,7	28,8	25,1
24 m	35,3	-27,6	15,7