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Three-Building and Typical City Multiple-Building Simulations

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Abstract

This paper summarizes research conducted in FY 2004 under High Performance Computing Modernization Program (HPCMP) DoD Challenge Project C-83 "Evaluation and Retrofit for Blast Protection in Urban Terrain." The ERDC is continuing the development of improved models for predicting the blast environment for high-explosive detonations in urban terrain. This is an integrated experimental analytical program, where high performance computing (HPC) simulations are used to assist in designing experiments. The experiments are used to validate the numerical simulations, and the validated numerical simulations are used to help in understanding the phenomenology associated with blast in urban terrain. The experimental and numerical research are used to develop engineering models that can be used to quickly predict effects of adjacent structures on the blast load on a structure of interest. The primary focus of the FY 04 research was the simulation of a blast environment for a collection of three buildings and the extension of the simulations to include a typical multi-building environment. This report summarizes the comparison of a three-building simulation with a companion experiment. Numerical simulations are then used to study the effects of five buildings and a typical city configuration of multiple buildings.

1. Introduction

Protecting our military personnel from terrorist attacks is critical to the US Department of Defense's (DoD) mission success as indicated by the selection of Combating Terrorism (CbT) as a Joint Warfighting Capability Objective (JWCO). The ERDC has developed the AT-Planner Software (US Army ERDC, 2001) to assist planners in evaluating the hazard to building occupants associated with a given terrorist threat. The AT-Planner Software also assists in designing retrofits to improve the degree of protection provided. While the AT-Planner is a useful design tool, it does not adequately model the complex problem of blast in urban terrain. For example, the effects of shock wave interaction with multi-structure environments are not addressed in the current AT-Planner models.

The presence of other structures can significantly affect the loads on the structure of interest. These loads can be decreased due to shielding effects or increased due to confinements or reflection of pressures off of these adjacent structures. An engineering model that accounts for these effects is needed for inclusion in the AT-Planner Software. Pursuant to this, a series of HPC simulations has been initiated to address airblast shadowing/reflections from adjacent structures. A companion series of small-scale experiments was conducted during FY 2003 and continued into FY 2004.

The FY 2003 experiments and numerical simulations (Bevins, et al., 2003) focused on the effects of barrier walls with berms and on the shielding of one structure by another. Two-building experiments where one structure is placed between the explosive and the structure of interest was conducted and the results were compared with companion single-building experiment and numerical results. The comparisons between the numerical and experimental results were very good and indicated that the numerical simulations captured the phenomenology of the shielding of one structure by another.

The FY 2004 experiments and numerical simulations studied clearing effects, effects of obliquity of shock front to structure, and focusing effects where adjacent buildings tend to focus the blast on the building of interest. When explosives detonate near a structure, the airblast reflects off of the structure causing an increase in the pressure loading on the structure. That reflection is relieved by a rarefaction wave propagating in from the nearest free edge. Current models, for example TM 5-855-1 (US Army, 1985) over-predict the amount of time required to relieve the reflected pressure, and thus over-predict the impulse applied to a structure. An improved method of predicting the relief of the reflected pressure has been developed based on experiments and HPC simulations conducted in FY 2004 under this DoD

Challenge Project. In almost all of the experiments conducted, the explosive charge is placed opposite of the center of the structure.

The reflected pressure and relief of the reflected pressure are affected by the angle of incidence. Simulations were performed for a range of incidence angles. In these simulations, the charge location varied from directly in front of the center of the structure to a location along a 45-degree line through the corner of the structure. In addition to these simulations, simulations were performed to assist in designing retrofits for a critical structure located in a complex urban environment.

Three-building experiments were conducted to study the focusing effect. In addition to the three-building experiments and simulations, HPC simulations were also conducted for a five-building urban environment where the explosives are confined between two structures and significantly focus the blast loads on one of the other structures. A multiple-building typical city was also modeled. In this case, both shielding and focusing effects are included in the same simulation. Comparison of three-building simulations to experimental data and the five-building and multi-building simulations are discussed in this paper. Comparisons with one- and two-building simulations will also be made.

2. Problem and Methodology

The loads on a structure are affected by the presence of nearby structures. Whether the load is decreased or increased and whether that change will be significant is determined by the relative locations of the structures, the sizes of the structures and the location and size of the explosive charge. It is impractical to conduct enough experiments to completely understand these complex interactions. A better approach is to use a combined experimental/analytical approach. A limited number of experiments are conducted and used to validate numerical models. Variations in numerical models can then be used to extend the database and to understand the phenomenology that affects the loads. Once theories are developed to explain the interactions, a much smaller number of experiments and simulations can be used to validate the theories.

The simulations reported in this paper were performed using high priority HPC computing time provided under HPCMP DoD Challenge Project "Evaluation and Retrofit for Blast Protection in Urban Terrain." This is the third year of that Challenge Project. In order for the simulations to be completed efficiently, the code used must scale well on large numbers of processors.

The Second-order Hydrodynamic Automatic Mesh Refinement Code (SHAMRC) (Crepeau, 1988) was used for the airblast calculations. SHAMRC is an Eulerian finite difference code refined for the express purpose of calculating airblast propagation. The code uses rigid boundaries to simulate the air/structure boundaries. This is much more effective than modeling the steel in the structure as a material and eliminates multiple materials in a cell. It also eliminates the need to model a large number of cells through the thickness of individual walls. Not modeling the steel increases the critical time step and improves efficiency of the code. The effects of modeling the steel test bed as a rigid boundary were explored by Armstrong, et al. (2002) in the first year of this Challenge Project. Those simulations indicated that predicted pressure based on the rigid boundary will be slightly higher than pressures based on the steel test bed. Version 3 of SHAMRC (Crepeau, et al., 2001) was used in the second and third years of the Challenge Project. In Version 3 of SHAMRC, the analysis domain is partitioned in three directions.

The simulations presented in this paper were performed on the Compaq SC40 and SC45 systems at the ERDC Major Shared Research Center (MSRC). The SC45 has 512 Alpha EV 68 processors with a processor speed of 1GHz and a peak computational performance of 1 TFlop/sec. The SC40 has 512 Alpha EV 68 processors with a processor speed of 833 MHz and a peak computational performance of 853 GFlop/sec.

Simulations were performed to assess the scalability of SHAMRC on the ERDC Compaq SC45. The analysis setup is a small-scale problem representative of an urban environment. A one kilogram hemispherical charge is located at the center of the mesh and four buildings are distributed symmetrically about the charge. The problem is scalable, which means as the number of processors increases, the number of cells increases to keep the same number of cells on each processor. The single processor mesh used ¼ symmetry with a mesh size of 101 by 101 by 100 for a total of 1,020,000 cells. The two-processor analysis doubles the problem size by using ½ symmetry with a mesh size of 201 by 101 by 100 for a total of 2,030,100 cells. The ideal number of cells should be 2,040,000. The difference between the ideal and actual values is less than 1 percent and remained consistent for all cases. Restrictions on the allowable mesh dimensions force this number to vary slightly from the ideal (the first two values must be odd, and the last value even). The results from the study are quite good for scalable problems. Obviously some overhead such as communications and increased number of ghost cells on processor boundaries introduce discrepancies between the ideal and actual grind times.

2.1. One-, Two-, Three-, and Five-Building Simulations.

The layouts for the one-, two-, three-, and five-building simulations are shown in Figure 2. The C4 hemispherical charge is always on the ground directly opposite the center of the large building (572 wide by 572 deep by 737 mm high) at a standoff of 846 mm. For the two-building simulation (Figure 2a) the small structure (336 wide by 336 deep by 458 mm high) is centered directly in front of the center of the large structure at a standoff of 206 mm from the charge. For the three-building simulation, the two small structures (labeled 3 in Figure 2a) are placed at the same standoff from the small charge, but the two small structures are 300 mm apart. For the five-building simulation, the two small buildings labeled 5 in Figure 2a were added. The structures are placed such that the explosive charge is opposite the center of the sidewalls of the structures and half way between them. Each model took advantage of the symmetry plane through the center of the explosives and the center of the large structure. The three-building model consisted of approximately 38 million cells to model the 9.5 square meter geometry. The 5 msec, three-building simulation required 540 GB disk space and 4,100 processor hours on 32 processors on the Compaq SC40. In the five-building simulation, data for animations were not saved. This reduced the disk space required to minimal. The 5 msec simulation of 40 million cells was accomplished in 527 processor hours on 64 processors on the Compaq SC40. A total of 12.6 square meters was modeled in this simulation.

2.2. Typical City Multi-Building Simulation.

The plan view and charge (5,000 kg C4) location for the multi-building simulation are shown in Figure 3. The simulation represents a 22,500 square meter portion of a typical city. The model consists of 158 million cells. The 334 msec simulation was performed on up to 64 processors and required a total of 19,432 processor hours and 2,500 GB disk space on the Compaq SC40.

3. Results

3.1. Three-Building Simulation.

Data recorded from the experiments and histories from the numerical simulations were scaled so that this paper could be published in open literature. For each gage location presented, the pressure history was divided by the peak pressure from the numerical simulation at the location of the gage. Impulse histories were scaled by dividing by the maximum impulse from the simulation, and the times were scaled by dividing by the time at the end of the positive phase for the numerical simulation. In general, the time of arrival for the numerical simulation was slightly lower than for the experimental data. The time of arrival for the numerical simulation was shifted to match the data so that the pulse shapes could be easily compared.

Pressure gages were provided in each of the experiments at five different heights along a vertical line through the center of the front face of the large building and one of the small buildings. The lowest gage on the small building is located at 76.2 mm off of the ground. Scaled pressures and impulses from the experiment were compared with scaled values for the numerical prediction. Time of arrival of the blast wave from the numerical simulation was slightly lower (13 percent) than from the experiment. The peak pressure and maximum impulse from the experiment are about 75 and 96 percent of the respective values from the numerical simulation. Scaled pressures and impulses are plotted vs. height off of the floor in Figure 4. The pressures and impulses were scaled by dividing by the respective values from the numerical simulation at the ground level. The pressures from the numerical simulation are slightly higher than the experimental values, except at the second to the lowest gage location where they are almost exact. Numerical impulses are slightly higher than the experiment at the lower gage heights, while the experimental values are slightly higher at the upper gage locations.

Scaled pressure histories for the lowest gage location on the front center of the large building were compared. The time of arrival of the numerical simulations was about 17 percent less than the time of arrival of the data history. In this case the measured peak pressure and impulse are 55 and 74 percent of the respective numerical values. Comparisons for other gages are much better. For example, for the gage just above the bottom gage, the measured peak pressure and impulse are 86 and 72 percent of the respective numerical values. The higher pressures in the simulation are consistent with the shorter arrival times.

Since the primary purpose of the analyses is to determine the effects of the surrounding structures, the ratio of the peak pressures (impulses) of the three-building simulation to the respective one-building pressures (impulses) are important. The ratio of peak pressure from the three-building simulation to peak pressure from the one-building experiment are plotted vs. height on the center of the large structure and are presented in Figure 5. These curves are labeled as the "Data, 3/1" and "Anal., 3/1" for the data and simulation, respectively. These curves show that the simulations provide the correct trends and provide conservative estimates of the effect of confinement on the pressures on the front of the large building. Both the analysis and the data indicate that the effect of confinement decreases with height on the building. The same trends are also true for the maximum impulse ratios.

The early-time pressure histories on the inside of the small building give an indication of the accuracy of the numerical simulation in predicting the effects of confinement. Scaled pressure and impulse histories at the location of the lower gage on the inside side of the small building are compared in Figure 6. The experimental peak pressure and impulse are 86 and 102 percent of the respective numerical values, indicating very good agreement between the simulation and the experimental data.

In the three-building experiment, a pressure gage was installed to measure side-on pressure on the table surface along the line between the charge and the center of the large structure at a distance of 546 mm from the explosive charge. This is approximately in line with the side of the small structure nearest the large structure. Thus, the pressure at this location is affected by the confinement of the two small buildings. The time of arrival for the numerical simulation was about 20 percent lower than the experimental value. The early-time peak pressure and impulse match with the experiment well, indicating that the effect of the confinement of the buildings is modeled reasonably well in the simulation.

Scaled pressure and impulse histories on the side of the large building near the bottom are given in Figure 7. These curves show that there is very good agreement between the numerical predictions and the data. Similar results were obtained for pressure and impulse histories on the back and top of the large building.

3.2. Effect of Adjacent Buildings on Back Building Front-Face Loads.

In this section, the peak pressure ratio for a given simulation for a given location is defined as the peak pressure at that location for that simulation divided by the peak pressure at that location for the simulation with the large building only. The impulse ratio is defined similarly. The peak pressure ratios at the center of the width of the large building are plotted in Figure 5. The three-building results have been discussed previously. The two-building results for the data "Data 2/1" and simulation "Anal., 2/1" show that the numerical simulation does a very good job of predicting the shielding effect of the small building on the peak pressures on the large building. The five-building simulations "Anal., 5/1" show the extreme effect of having the weapon confined between two buildings. Experiments have not been conducted for this configuration. This curve shows that the peak pressure could be as high as 3.75 times the single building pressures and that the increase in pressure caused by the confinement does not drop off significantly with height on the building. The numerical simulation does a very good job for the ratio of impulse for the two-building case.

Fringe plots of peak pressure ratios on the front of the large building front wall are given in Figure 8. Figure 8a shows that the peak pressure for the two-structure case is always less than 75 percent of the peak pressure that would be present for the one-building case. Near the bottom center of the building, the peak pressure is less that 25 percent of the one-building value. The peak pressure is less than half of the one-building pressure over most of the structure face. Only near the top center of the building does the pressure exceed half of the one-building value. Maximum impulse ratios are shown in Figure 9. Figure 9a shows that the impulse near the bottom center of the two-building simulation is between 25 and 50 percent of the impulse of the one-building case. Near the edges of the building and near the top center of the wall, the impulse is between 50 and 75 percent of the one-building value. In very small areas near the top edges of the wall, the impulse ratio is between 75 and 100 percent.

Pressure and impulse ratio fringe plots for the three-building simulation are shown in Figures 8b and 9b, respectively. Very near to the bottom and center of the building, the pressure for the three-building simulation is between 2.25 and 2.5 times the single-structure pressure. The peak-pressure ratio drops off very rapidly with horizontal distance from the center of the wall. At a distance approximately equal to the location of the inside surface of the small building, the peak pressure near the bottom has dropped off to approximately equal to the one-building peak pressure. Near the edges of the building, the peak pressure ratio drops to between 0.75 and 1.0. For a very small area near the center of the bottom of the wall, the impulse is between 1.5 and 1.75 times the one-building value. Near the bottom, the impulse ratio drops to 1 at about the location of the inside wall of the small structure. Near the edges, the impulse ratio drops to between 0.5 and 0.75. Near the horizontal center of the wall, the impulse ratio drops to between 1.0 and 1.25 near the location of the height of the small building.

The pressure and impulse ratios for the five-building simulation are shown in Figures 8c and 9c, respectively. Figure 8c shows that near the center of the wall, the peak pressure exceeds 3 times the one-building pressure for the full height of the building. The pressure ratio exceeds 2 over most of the wall. Near the center bottom of the wall, the impulse ratio exceeds 2.25 and the impulse ratio exceeds 1 for the entire wall.

3.3. Typical City Multiple-Building Simulation.

Peak pressures and maximum impulses were extracted from target point locations on each surface of each of the structures in the simulation. The peak pressure for each of the target points is plotted against the range to that target in Figure 10. These results are compared with the airblast standard (Kingery and Bulmash, 1984) as provided by the Conventional Weapons Effect (CONWEP) (Hyde, 1992) computer code. This figure shows that in some cases the peak pressure exceeds the CONWEP reflected pressure. Pressures exceed the fully reflected pressures because those areas are directly exposed to the blast and the blast is enhanced by confinement. In many cases, the peak pressure is between the CONWEP incident and reflected pressures. In most cases, the pressures are below the CONWEP incident pressures. These are locations that are not directly exposed to the blast. The blast may have to propagate around several buildings. In some cases, the peak pressure is an order of magnitude below the CONWEP incident peak pressure. Figure 11 was developed for maximum impulses. A few impulses are above the fully reflected values, many are between the reflected and incident, and most are below the incident impulse. These comparisons clearly demonstrate the need for improved engineering models for blast in urban terrain. The current models could lead to designs that are non-conservative or to designs that are an order of magnitude conservative, thus causing an allocation of funds to retrofit a wall that may not need it. Several additional typical city multi-building simulations are needed to evaluate the effects of neighboring structures on the loads on the structure of interest in a realistic urban terrain.

4. Significance to DoD

The two-, three-, five-, and multi-building simulations demonstrated the need for accounting for adjacent buildings when determining the loads on the structure of interest. Comparisons with experimental data indicated that the simulations provided conservative, but reasonable, estimates of the effects of surrounding structures on the loads on the structure of interest.

The numerical simulations presented will lead to improved methods of predicting loads on structures in urban terrain. In some cases, the improved method will replace a non-conservative method and thus provide additional safety for our troops housed in these structures. In other cases, the improved predictive methods could allow troops to stay in buildings that would not be determined to be safe based on overly conservative estimates of the loads. This will lead to improved safety of our troops in urban terrain.

Better methods of predicting loads in urban terrain will also lead to better estimates of collateral damage when we are targeting a structure in urban terrain.

5. Systems Used

Compaq SC40 and SC45 systems at the ERDC MSRC.

6. CTA

Computational Structural Mechanics

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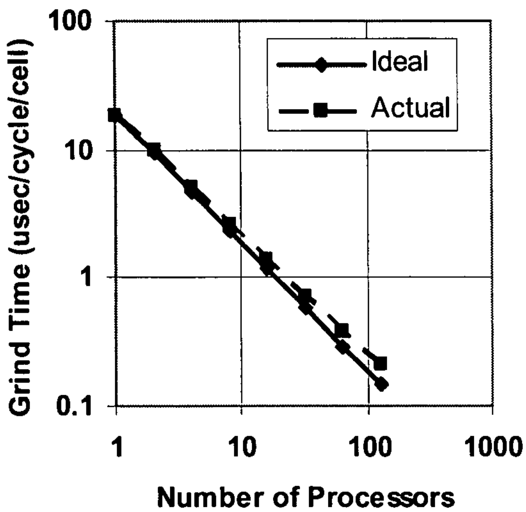
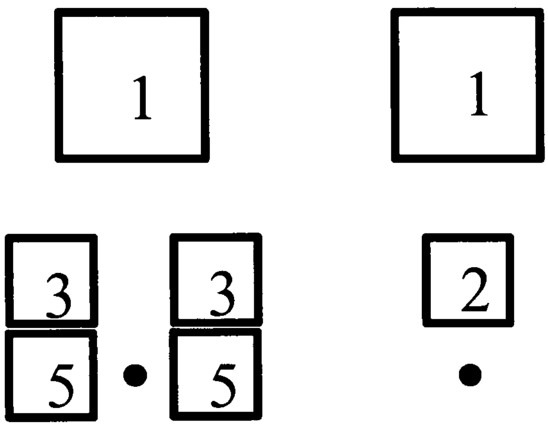


Figure 1. Scalability study for SHAMRC



a) One-, Three-, Five-   b) One-, Two-

Figure 2. One- to five-building layouts

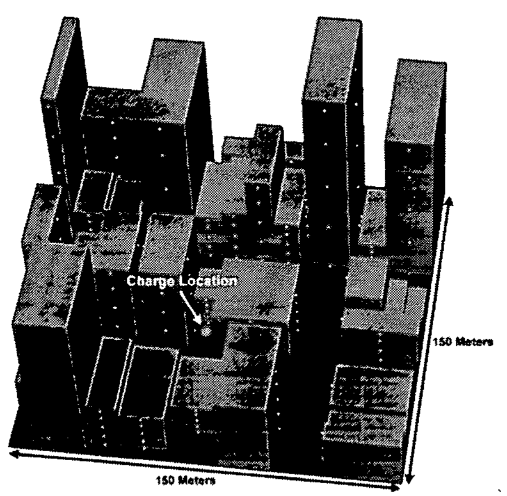


Figure 3. Typical city multi-building layout

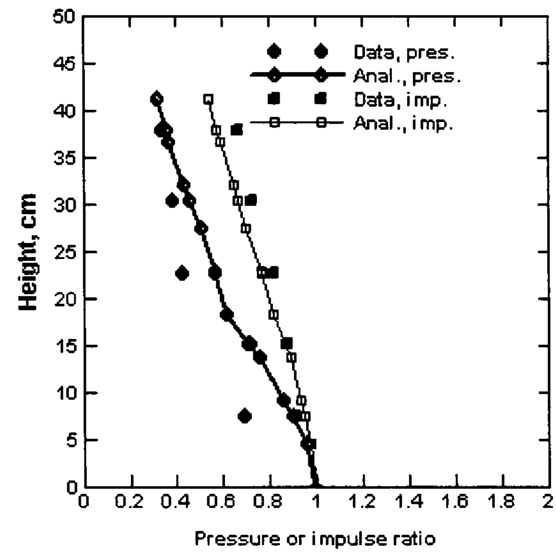


Figure 4. Scaled pressure and impulse, front of small structure

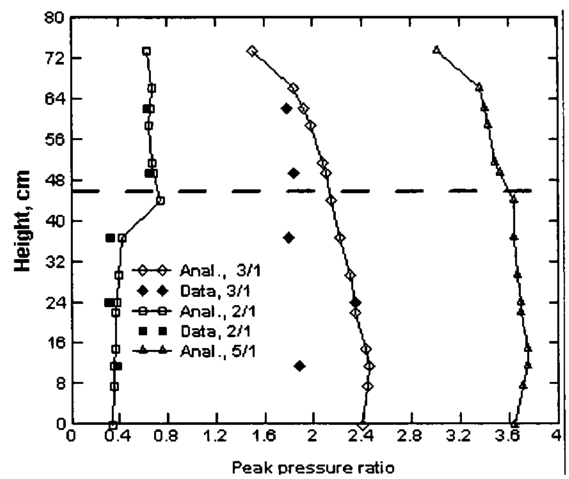


Figure 5. Scaled pressure, front of large structure

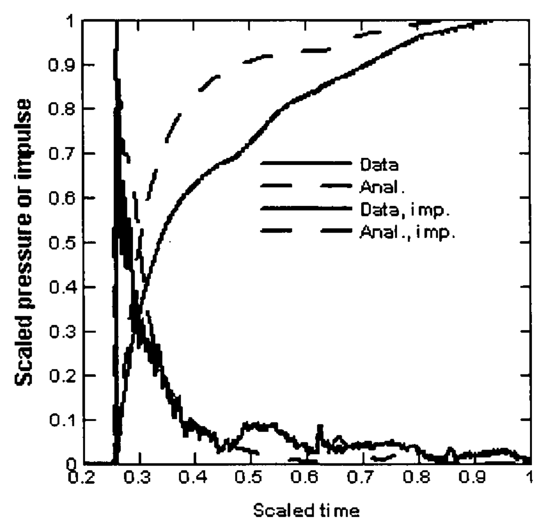


Figure 6. Pressure history, inside wall of small structure

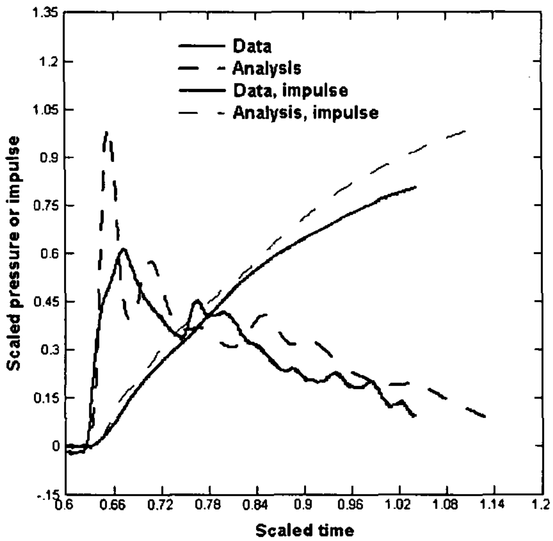


Figure 7. Pressure history, side of large structure

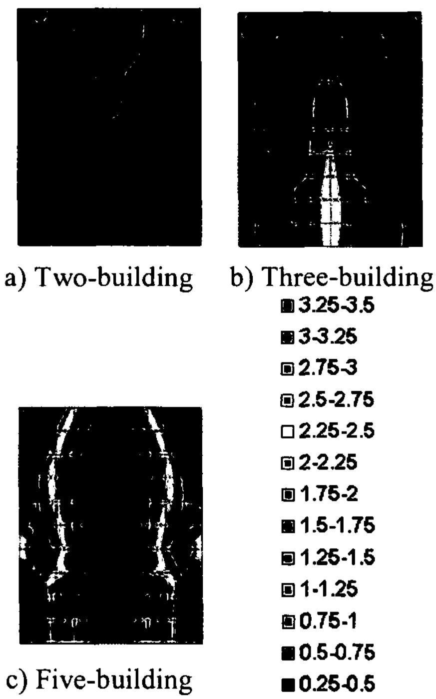


Figure 8 Pressure ratio plots, front of large structure

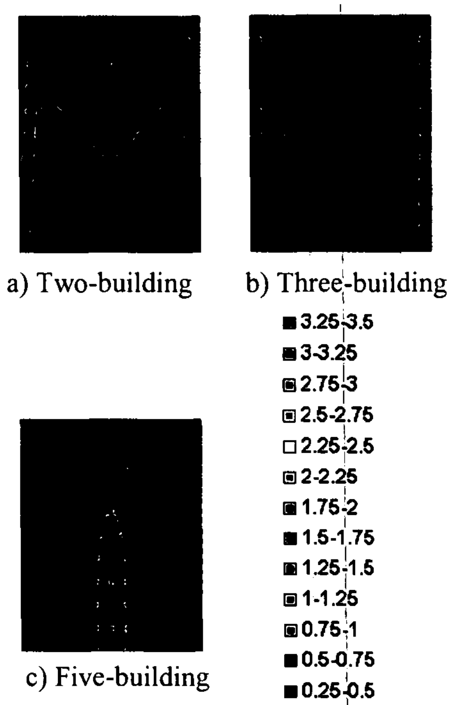


Figure 9. Impulse ratio plots, front of large structure

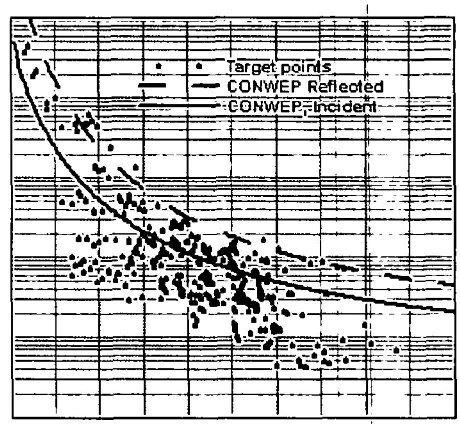


Figure 10. Pressure vs. range for typical city

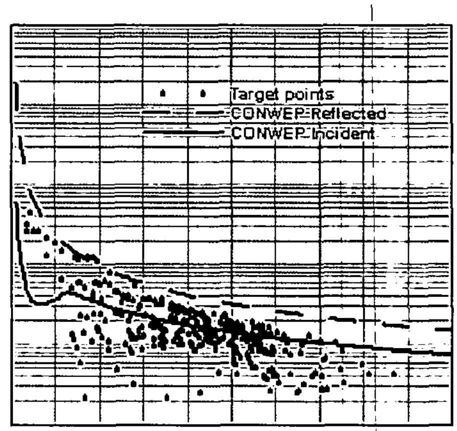


Figure 11. Impulse vs. range for typical city