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Title: Underground Infrastructure Impacts Due to a Surface Burst Nuclear Device in an Urban Canyon Environment

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Report

Underground Infrastructure Impacts Due to a Surface Burst Nuclear Device in an Urban Canyon Environment

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Methods and Algorithms Group

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Executive Summary

Investigation of the effects of a nuclear device exploded in a urban environment such as the Chicago studied for this particular report have shown the importance on the effects from the urban canyons so typical of today's urban environment as compared to nuclear test event effects observed at the Nevada Test Site (NTS) and the Pacific Testing Area on which many of the typical legacy empirical codes are based on.

This report first looks at the some of the data from nuclear testing that can give an indication of the damage levels that might be experienced due to a nuclear event. While it is well known that a above ground blast, even a ground burst, very poorly transmits energy into the ground (< 1%) and the experimental results discussed here are for fully coupled detonations, these results do indicate a useful measure of the damage that might be expected.

The second part of the report looks at effects of layering of different materials that typically would make up the near ground below surface environment that a shock would propagate through. As these simulations support and is widely known in the community, the effects of different material compositions in these layers modify the shock behavior and especially modify the energy dispersal and coupling into the basement structures.

The third part of the report looks at the modification of the underground shock effects from a surface burst 1 KT device due to the presence of basements under the Chicago buildings. Without direct knowledge of the basement structure, a simulated footprint of a uniform 20m depth was assumed underneath each of the NGI defined buildings in the above ground environment. In the above ground case, the underground basement structures channel the energy along the line of site streets keeping the shock levels from falling off as rapidly as has been observed in unobstructed detonations. These simulations indicate a falloff of factors of 2 per scaled length as compared to 10 for the unobstructed case. Again, as in the above ground case, the basements create significant shielding causing the shock profile to become more square and reducing the potential for damage diagonal to the line of sight streets. The results for a 1KT device is that the heavily damaged zone (complete destruction) will extend out to 50m from the detonation (~100m for 10KT). The heavily to moderately damaged zone will extend out to 100m (~200m for 10KT). Since the destruction will depend on geometric angle from the detonation and also the variability of response for various critical infrastructure, for planning purposes the area out to 100m from the detonation should be assumed to be non-operational. Specifically for subway tunnels, while not operational, they could be human passable for human egress in the moderately damaged area.

The results of the simulations presented in this report indicate only the general underground infrastructure impact. Simulations done with the actual basement geometry would be an important improvement. Equally as important or even more so, knowing the actual underground

material configurations and material composition would be critical information to refine the calculations. Coupling of the shock data into structural codes would help inform the emergency planning and first response communities on the impact to underground structures and the state of buildings after the detonation.

Historical Experimental Results from the Nevada Test Site

Many documents that describe the blast effects on underground structures reference complete destruction from overpressures of .25-1KBar with the range depending on the surrounding material the underground structure is imbedded in. These values are derived from a number of NTS events that either were specifically designed to look at structure failure or where observed from underground tunnel tests. The two tests that are most quoted are ones that specifically had various shaped and reinforced underground structures located at some distances from the source. These are the tests Hard Hat and Pile Driver[1]. It should be noted that these are examples of completely coupled explosions which means the energy of the source is almost completely absorbed by the surrounding rock. It should also be noted that experts on modern underground structure resilience to shock damage believe the NTS experimental results are not generally applicable to other scenarios[2]. While not shared universally, this opinion does feed into the observation that structural analysis calculations driven by strong shock calculations for the above ground urban nuclear event where the coupling is very dependent on surface ground type is an important next step in these type of analysis.

Plan View – HARD HAT

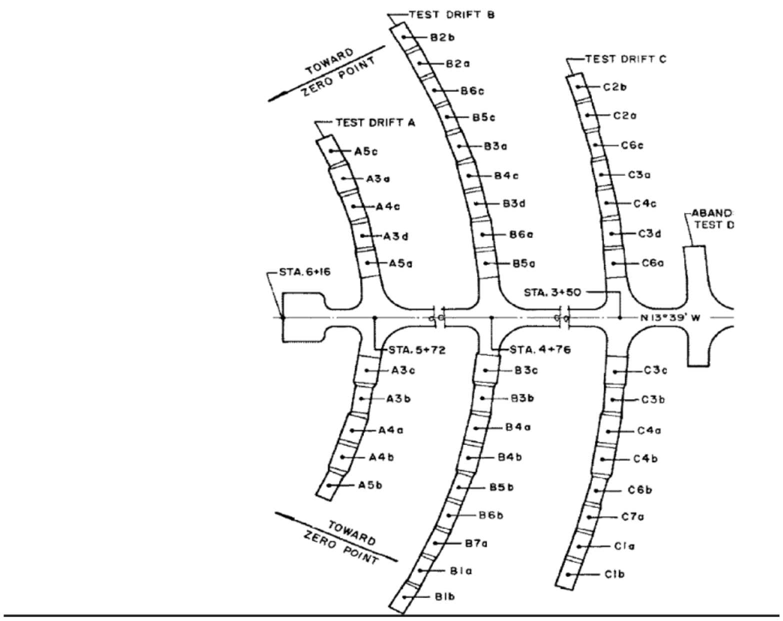


Figure 1: Experimental Configuration of underground test structures

Elevation –HARD HAT

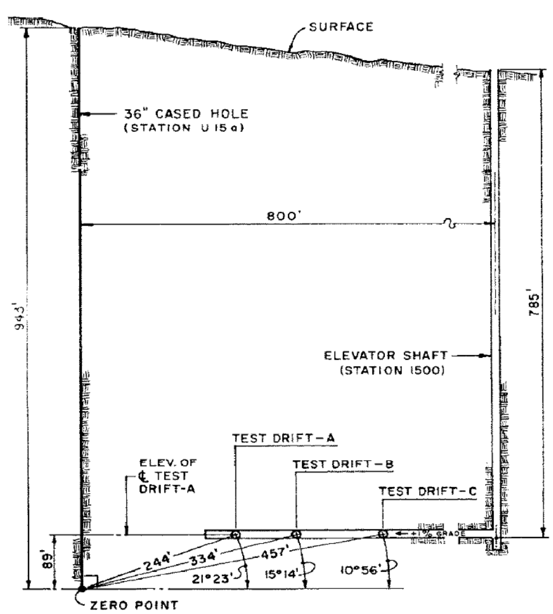


Figure 2: Distances to Test Drifts from the source location

The Pile Driver and Hard Hat tests were extensively analyzed[1]. Over pressure values that are now standardly quoted for total destruction of underground structures of .25-1 KBar depending on surrounding rock composition come from this analysis. There were also values for peak velocities when various levels of damage occurred (another variable usually available in modern hydrodynamic codes) but the physical variable that most indicated damage level was the accumulated strain rate which was independent of surrounding material type. This report will use the overpressure indication to estimate damage levels because an error was found in the code outputting the values and could not be corrected in time to change in this report. Future work, if funded, will use the strain rate levels described in 1).

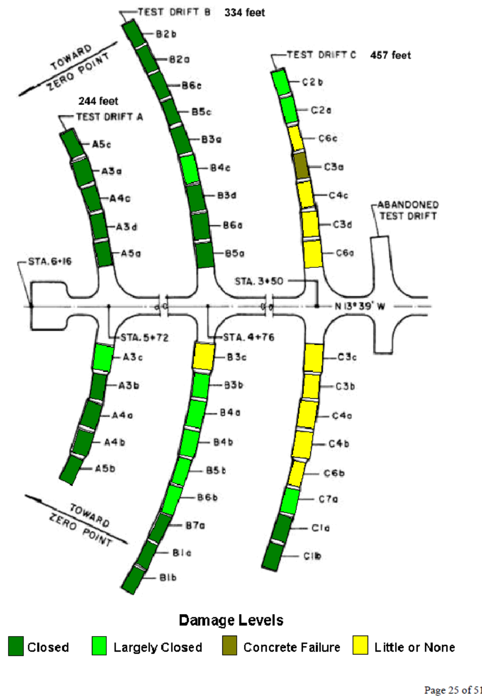


Figure 3: Color Coated Damage Results for Hard Hat [1]

Figures3 and 5 are very descriptive representations of the various damage levels experienced in the various drifts for Hard Hat and Pile Driver. Each drift should have experienced roughly the same over pressure at each location right and left off the main drift. Thus the difference in damage can be explained mainly by the construction type. For this study the distances away from the explosion point is the most important feature. Within a distance of roughly 60 meters damage for the same construction type goes from completely to lightly damaged.

Perspective of PILE DRIVER

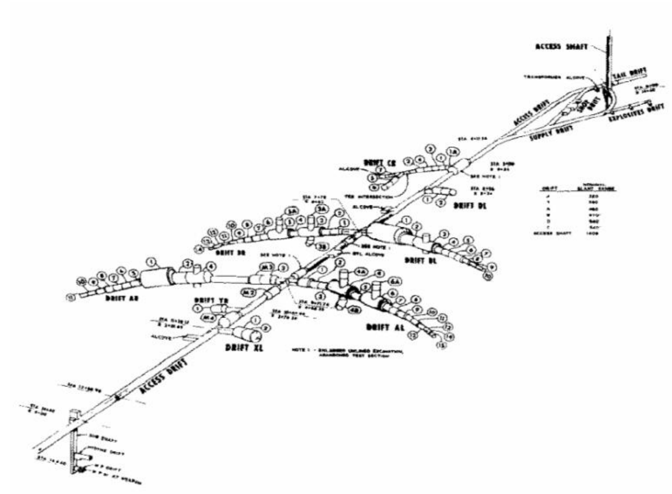


Figure 4: Experimental Structures Location for Pile Driver and source location[1]

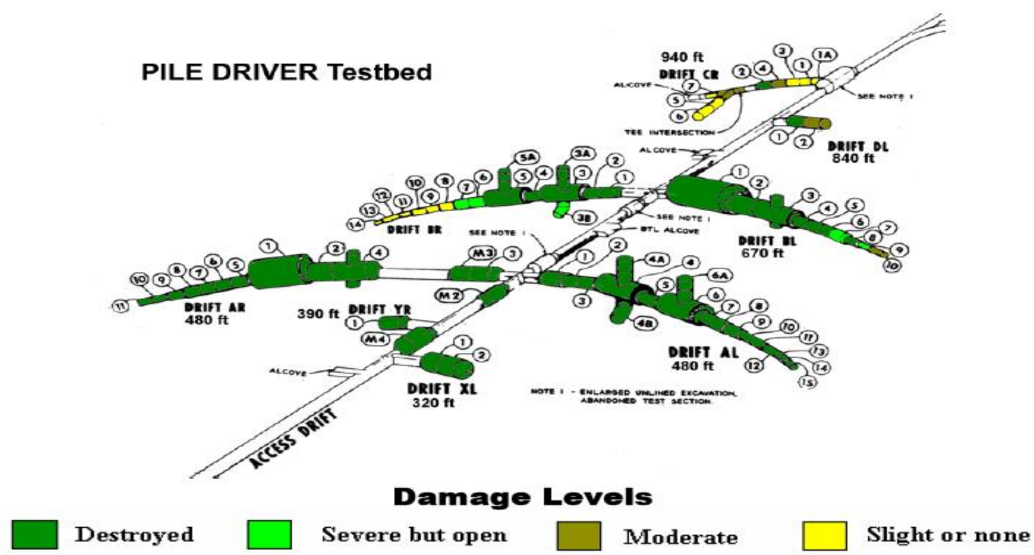


Figure 5: Color Coated Test Results[1]

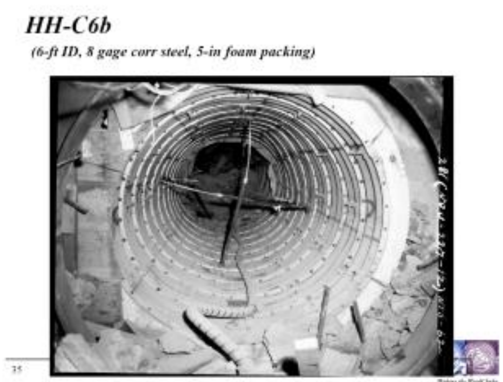
Abbreviations		Steel Plate Thicknesses		
Symbol	Meaning	Gage	Inches	mm
C	Concrete	8 Ga.	0.164	4.17
CSC	Concrete-Steel-Concrete	7 Ga.	0.184	4.67
CC	Concrete-Concrete Sandwich	3 Ga.	0.245	6.22
SC	Steel-Concrete Composite	1 Ga.	0.276	7.01
S	Steel	3/8"	0.375	9.52
RB	Rock Bolts + Chain Link Fab.	Test Section Addresses		
U	Unlined	Symbol	Meaning	Range (ft)
H	Horizontal	A	A Drift	480
V	Vertical	B	B Drift	670
CAP	Capsule, tilted 45° to WP	C	C Drift	940
X	Cross Intersection	D	D Drift	840
T	Tee Intersection	X	X Drift	320
a	Cellular Concrete	Y	Y Drift	390
b	Polyurethane Foam	e	end-on	CR6e - 846
c	Cinders	e	end-on	CR5e - 866

Figure 6: Pile Driver Test Chamber Wall Construction[1]

The photos in figures 7 and 8 show what kind of damage is being indicated by the color coding in figures 3 and 5. Moderate damage would result in a tunnel (e.g. subway) that was still passible to survivors of the event. This will be discussed further in the conclusion section.

Heavy Damage Level (Dark Green: Destroyed)

Moderate Damage Level



Light to No Damage

Figure 7: Photos of damage levels after detonation for Hard Hat[1]

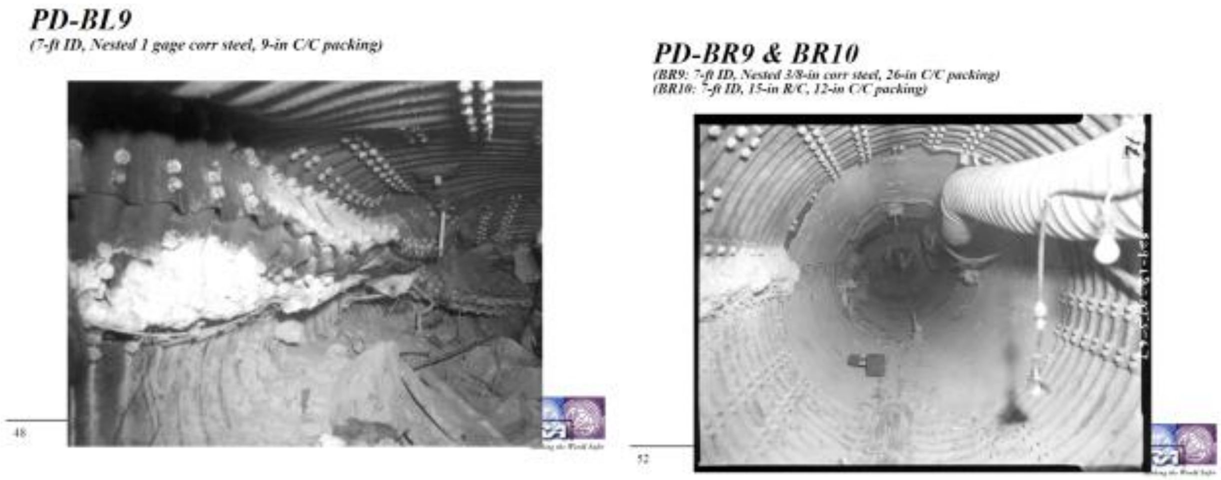


Figure 8: After Pile Driver event photos of damage suffered for select chambers[1]

When normalized (roughly) to a yield of 1KT and a surface burst event, the radiuses for the drifts in Hard Hat become 15m, 21m, and 28m respectively The values for Pile Driver become 11, 19, and 27m respectively. When normalized to 10KT and a surface burst event, the radiuses for the drifts in Hard Hat become 32m, 45m, and 60m respectively. The values for Pile Driver become 24, 41, and 58m respectively. This indicates for the type of rock (granite) that these tunnels were imbedded in that we would expect to see the same completely damaged, moderately damaged, and lightly damaged behavior for urban underground structures such as large piping, conduit chambers, and tunnels.

An analogous test regime for buried cables and small underground conduits would be the TTBT CORRTEX experiments. In these tests, horizontal cables that would crush at .01 to .1 KB were buried typically 10m, 20m, and 50m from a nuclear test. RF signals were sent down the cables and when the cables crushed from the shock impacting them the cables would become electronically “shorter” so that the time of arrivals of the reflected signal would indicate the shock front progressing radially away from the source. The .1 crush threshold also indicated roughly the transition from inelastic to elastic material response. In most ground materials that tests were performed in, the behavior of the crushed cables was typically uniform if the overpressure was above 1 KB and jagged if below. This is some what lower damage levels but roughly the same behavior observed in the tunnels discussed above. We will use the elastic and inelastic regimes to indicate completely damaged and moderately damaged transition.

2D and 3D Simulation Results for an Urban Underground Environment

2D Simulations in homogenous and layered ground: the effects of ground layering.

To show the differences between locations with different geophysical properties (such as layering of materials), several two dimensional calculations were performed. As such these are equivalent to what hydrodynamacists call flat field calculations where there are no obstructions.

Figure 9 shows two of these calculations. Both are 1 Kt sources placed 1 meter above the ground. Both are at .01s after the source detonation.   The length scale is 400m is each direction. The upper half of each is air. The lower half is ground with the left being in homogenous weathered granite and the right is three layers. The layers for the right are a clay layer at the surface followed by a more porous sedimentary layer and finally the same granite as the left. The scales on both are slightly different to bring out the salient parts of each calculation for comparison (such as the layers on the right). Note that underground shock in the both simulations has outrun the air blast. Also note that the ground shock propagation speed and therefore the energy is much slower in the layered material then in the pure granite. This is a representation of the differences in sound speed of the three layered materials.

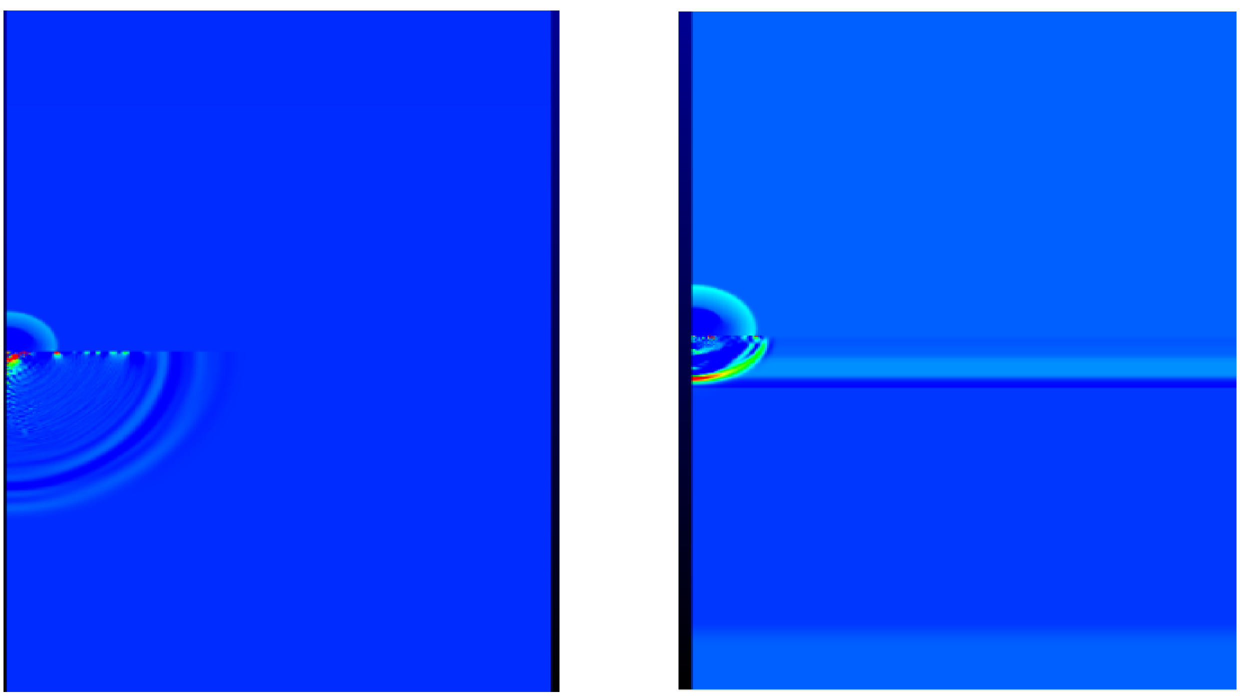
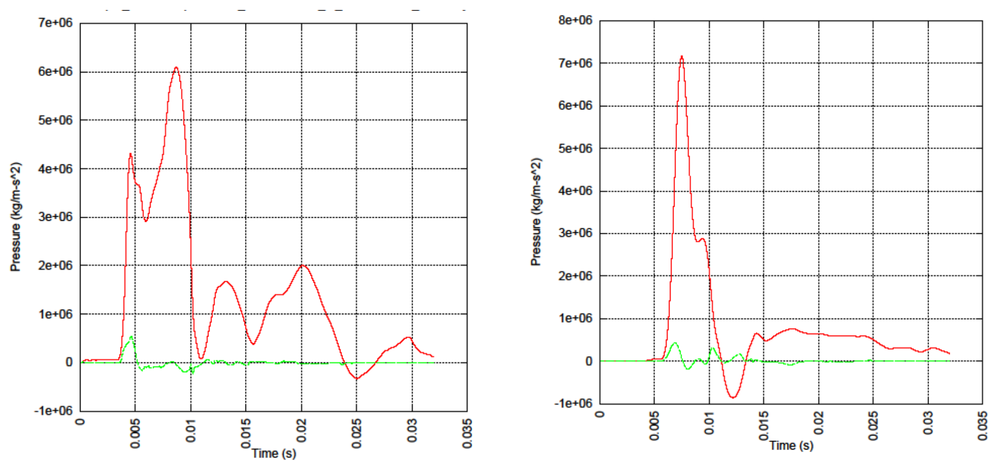
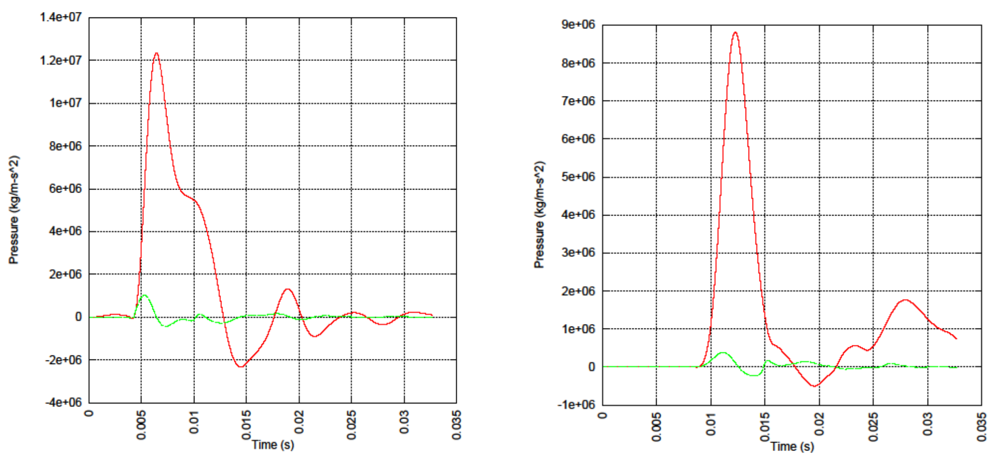


Figure 9. A 1 kt ground burst explosions at ~.01s. The top half of each figure is air. The bottom half of the left one is homogenous weathered granite. The bottom half of the right has 3 layers of material. The top layer is clay, followed by sediment, followed by granite again. The scales have been changed to emphasize the ground shock and layering.



Figures 10 and 11. Pressure profiles at 50 m radius from source. Both are from the homogeneous granite calculation. The left is at -1 m depth and the right is at -25 m depth.



Figures 12 and 13. Pressure profiles at 50 m radius from source. Both are from the multi-layer calculation. The left is at -1 m depth and the right is at 25 m depth.

Figures 10-13 show, first, differences between the near surface shock and, second, the difference between a single ground material and a layered situation (which would be the most common in an urban environment near the surface). One has to be somewhat cautious of the results of the near surface simulations simply because the hydro code used for these simulations is a continuum code. This means even though the physics says the material close to the explosion should be thrown up into a crater; the code itself cannot break up the material in way that realistically captures the cratering process. Part of the resultant waveform represents the attempt by the code to capture the cratering but, failing, starting to force the energy in other directions. Irrespective there is a ground/air interaction at the surface that complicates the wave structure as it propagates out. Figure 11 represents more of the ideal case of a shock propagating through a single material. Figures 12 and 13 represent the complicating effects of material layering. When the sound speed of the material is different in adjoining layers one will see reflections of the shock at these material boundaries. Further if the material sound speeds are very different between the layers one will see channeling of the energy in these layers. Typically a relatively uniform non-fractured material like granite will have a higher sound speed than a porous non-uniform material like soil, clay, or sediment (in fact this is why a relatively small earthquake on the east coast effected such a large area as opposed to those out west of higher magnitude). As can seen in the 2D pictures and the figures, the energy is indeed channeled with a higher energy remaining in the surface layers (meaning higher pressure) and a lower pressure at the 25m below ground level. Figure 14 below shows how the pressure is impacted by the multiple reflections and channeling at 100m from the detonation.

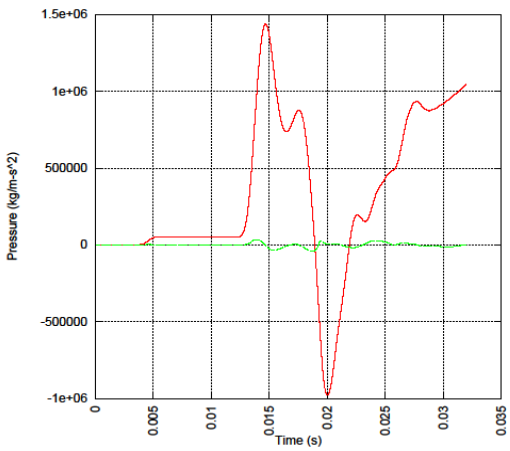


Figure 14. Pressure profiles of the multilayer calculation at 100m radius from source and a depth of 25m.

The overall point to be made here is that the geometrical and material makeup of the ground underlying the blast is a critical component to estimating damage to the infrastructure. Most of the underground infrastructure including much of any subway system is created in a excavated channel that is then refilled with material that is not the same as the material that was excavated, either because it was broken up during the excavation or refilled with some more suitable material. The same is true for many modern towers that have a fill layer around their basement structures. All of this will modify the blast effects and differentiate it from the NTS results mentioned in the discussion of PileDriver and HardHat experiments earlier in this document. It is the author's opinion that these effects should be more directly modeled than the funds allotted for this study allowed.

3D Urban Simulations in homogenous ground

A 3D variation of the simulations shown in the 2D section was performed extending Chicago's above ground building profile to a uniform basement structure with a depth of 20m from the surface. This was done as the analog of the above ground urban canyon environment and in the absence of the similar NGI database information for the real basement structure. The intent here was to again show the effect of basements on channeling energy and answering the question about enhancements to the shock from reflects off the buildings as is seen in the above ground air blast simulations. Figure 15 shows the below ground configuration of the simulation. The above ground city profile is removed for clarity. The physics variables are also removed for clarity.

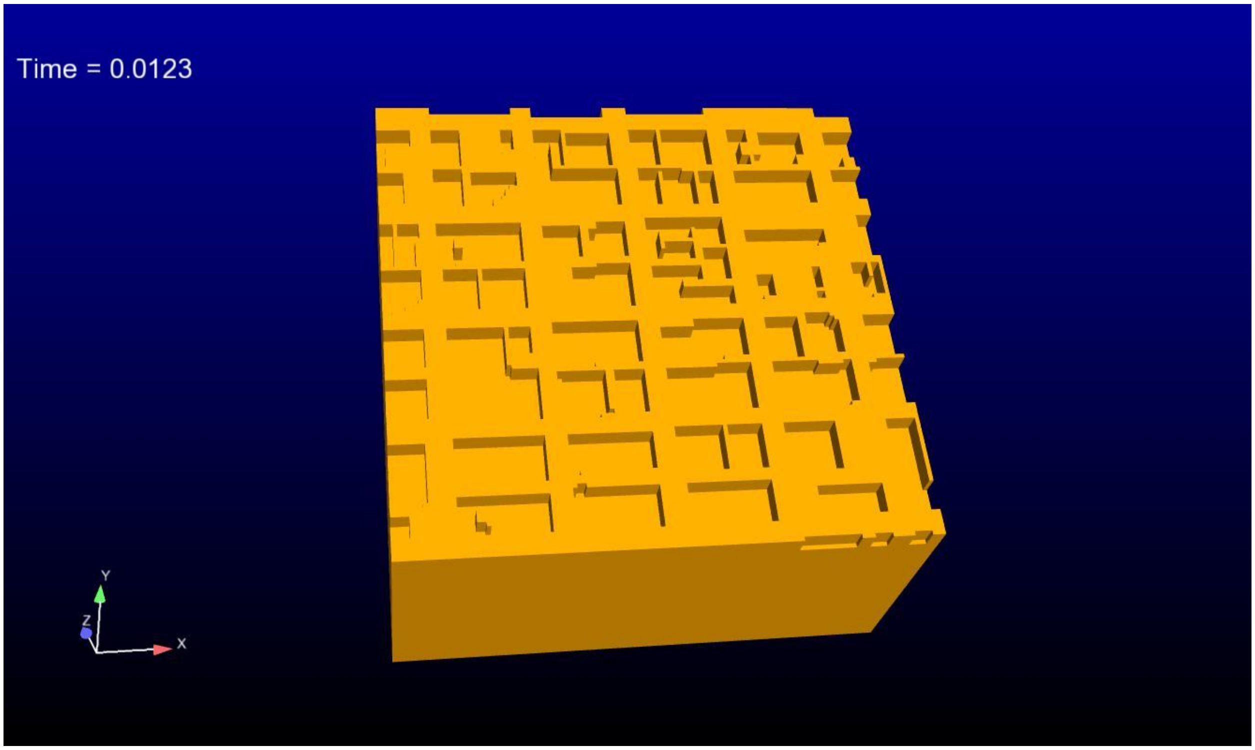


Figure 15. 3D simulation of a ground burst 1KT device in Chicago. An artificial basement structure of uniform depth has been extended below ground based on the above ground NGI building representation. The above ground part of the simulation has been removed for clarity.

For the simulation, cratering was suppressed to allow the calculation to run in a reasonable amount of time. The effect of this suppression is to reduce the peak pressures by about a factor of 10. Cratering in a continuum code such as the Lagrangian/ALE LANL research code CASH is at best an approximation to the effects of excavating and moving the ground directly underneath the ground burst device. The effect of the code trying to simulate the cratering process is a reduction in the calculational time step by factors of 100 or 1000. For this simulation, cratering was not the effect to be studied. While an important aspect of the total effect of the nuclear detonation, in a homogenous ground material as modeled here and just impacting the nearest buildings, the NTS derived cratering formulas would still be valid. What is shown in figure 16 is the size of the crater as derived from those formulas. This is presented to give an idea of the size of area where the underground infrastructure would be completely destroyed.

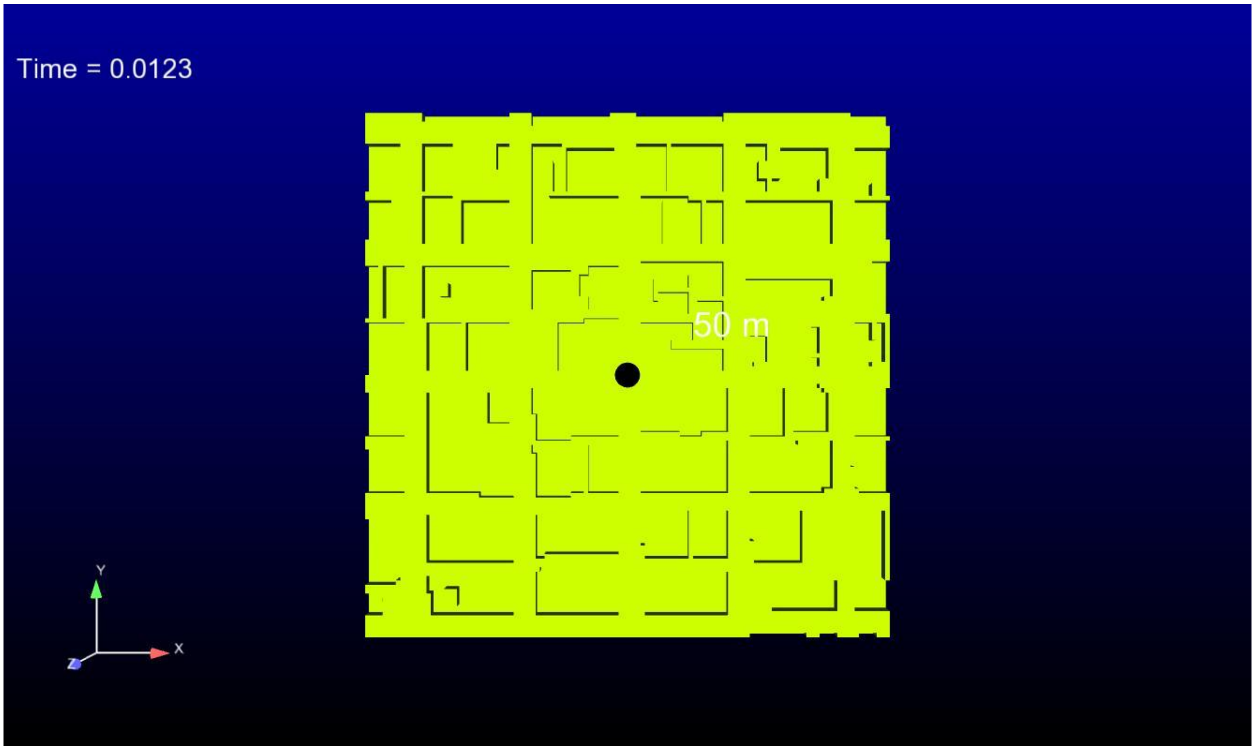


Figure 16. Size of the resulting crater superimposed on the calculational mesh. Cratering was suppressed in this calculation to allow the simulation to run in a reasonable amount of time. This view is directly above the detonation looking down. Outlines of the basement structures are visible

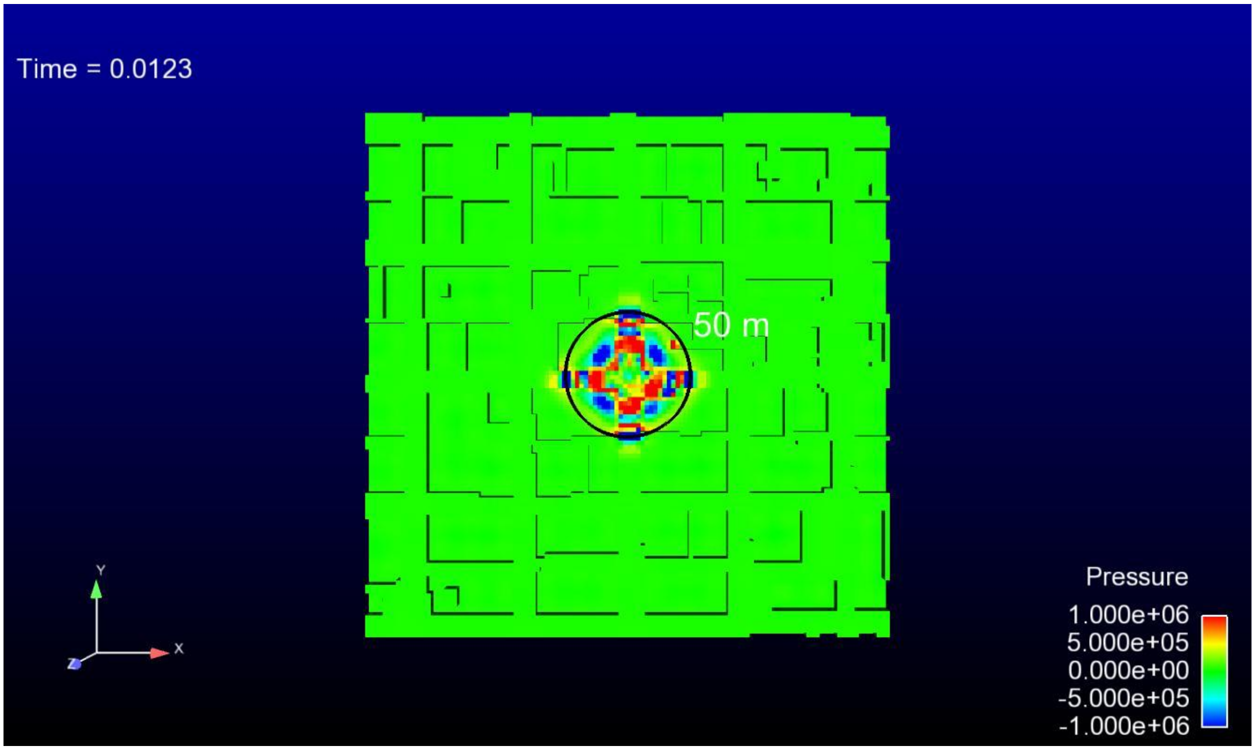
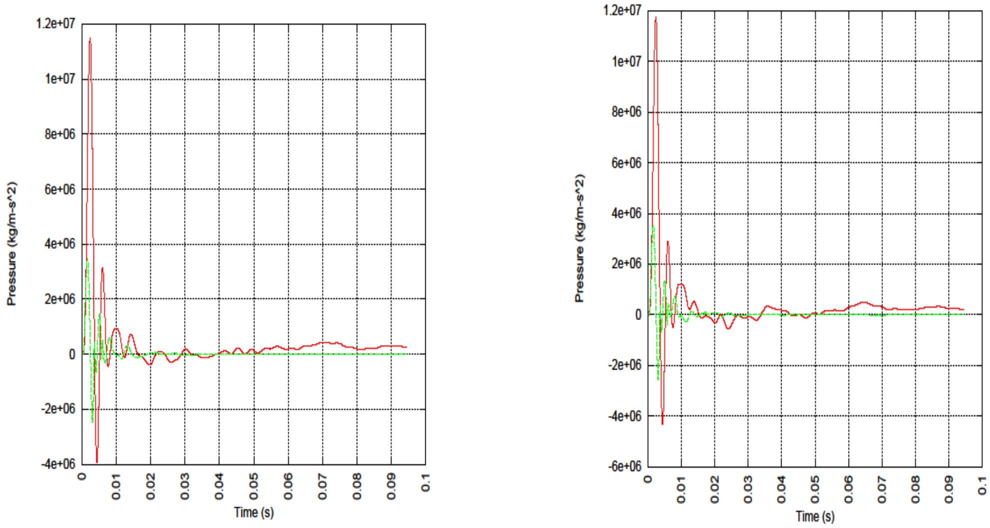


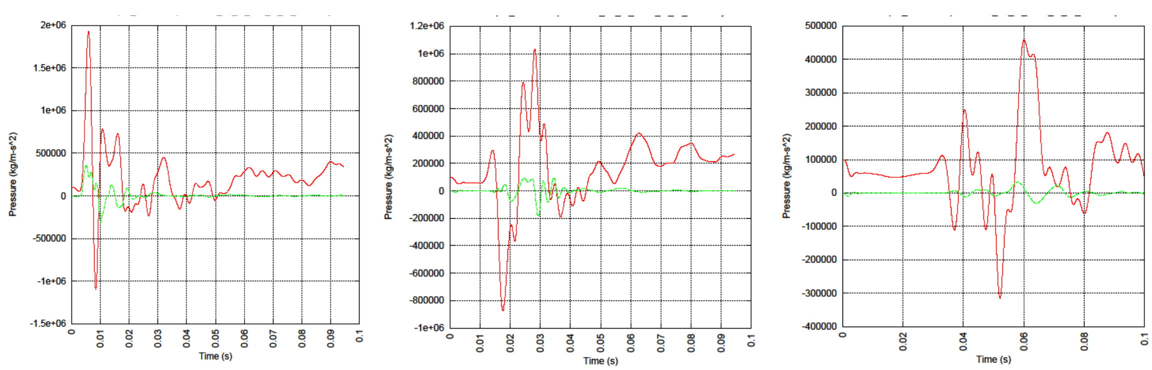
Figure 17. At 12 milliseconds after the explosion, the circle of complete destruction extends out to 50m. The scales have been fixed below maximums to emphasize the urban canyon channeling. See figures 18-19 for line plots of the pressure profiles.

The extent of complete damage can be estimated by the shock pressure values at the time the shock passes a given location. Close in to the event and in the line of sight down the streets the shock has the classical free field profile (no buildings present) and, indeed, follows the shock level estimates one would see out of legacy underground shock simulation codes. This can be seen in figures 18 and 19 where pressure profiles are taken 20 m to the left from the detonation and 20 m up from the detonation in the middle of the streets that have a line of sight to the detonation. Pressures in this region (1- 2 Kbar peak) are sufficient to cause heavy damage. Most if not all cables, pipelines, and other substructures would be destroyed in this area. The basement structures also would be heavily damaged if not completely demolished likely causing the building to collapse (although the air blast will also have caused the building to collapse).



Figures 18 and 19. Respectively, pressure profiles at locations 20m to the right and up the streets from the detonation shown in figure 17. Note the classic shock profile. Also note the radial symmetry before .02 s after reflections start to alter the symmetry. Values here are a factor of 10 reduced in order to suppress cratering as discussed in the main text.

As we look further away from the detonation location we see the effects of reflection off the basement walls. We also see that the flat field exponential decay is not seen down the city streets (compare figures 20, 21, and 22 specifically). We would expect roughly a factor of 8-10 decrease from 50 to 100m and 100m to 200m where we are actually seeing a factor of roughly 2 between the three locations. As in the above ground urban canyon air blast effects, the energy is being channeled down the city streets and is kept at a higher level than would be the case if there are no obstructions. It also should be noted that while being kept at a higher level, there is no indication of enhancement. In addition the waveforms are clearly made more complex as the shock is reflected off the basement walls.



Figures 20, 21, and 22. Respectively, pressure profiles at locations 50m, 100m, and 200m up the street from the detonation shown in figure 17.

The heavy to moderate damage zone can be seen in figure 23 from the circle indicating 50m out to 100m. At .05 s the shock pressure has fallen to below the moderate damage level as defined in section 1 above. Using this roughly as guidance, the effect on infrastructure will be varied. While specific response is outside the scope of this study, indications are that the damage will be varied even for infrastructure that normally would be expected to withstand these pressures. Subway structures will likely be passable for human egress at this point (see figure 8) but not operational. For planning purposes this area should also be considered to have no functioning critical infrastructure available.

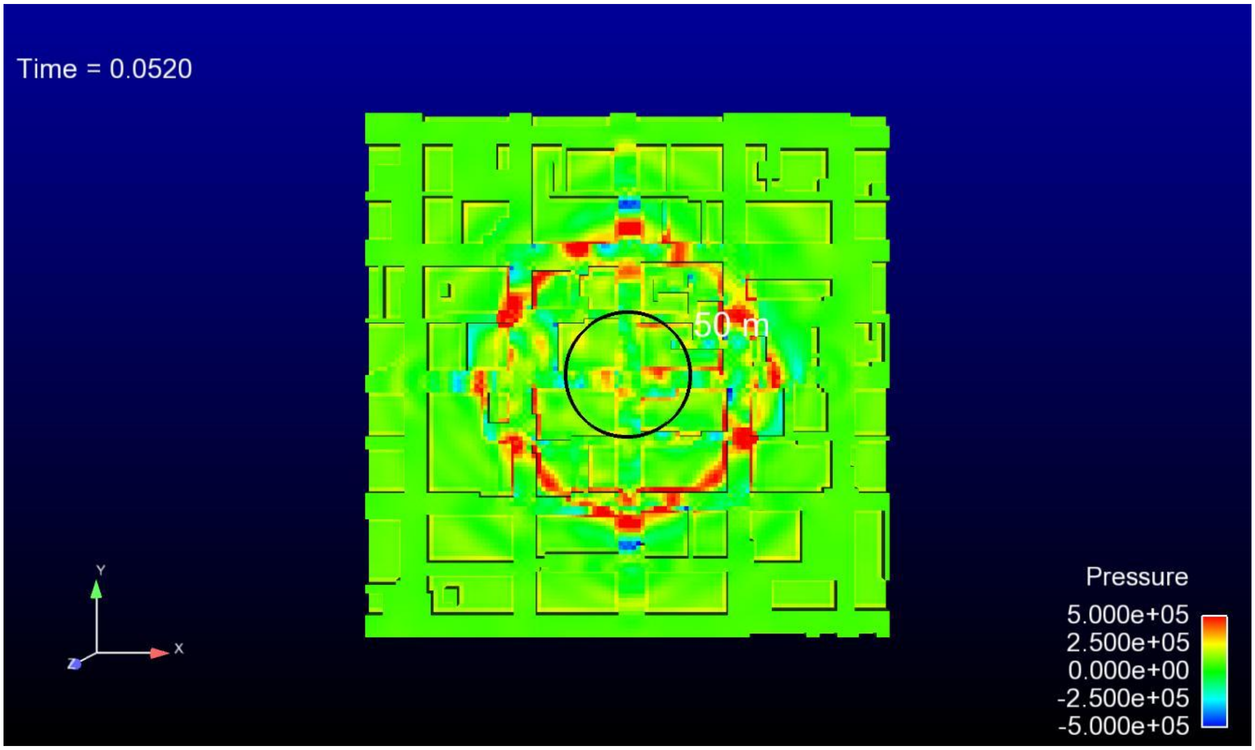


Figure 23. Pressure shock profile from above at .05 s. Moderate damage zone between 50m and 100m from the detonation point.

Figure 24 denotes the underground urban canyon effect is some detail. This shows peak accelerations over the total time of the simulation (.1s). The channeling of energy down the streets is visibly pronounced. Individual building effects (non-uniformity of building locations) can be seen as well to the NW of the detonation. Basement shielding just as in the above ground case is also readily seen with the physics effects taking on a square shape. The coloring indicates the region of heavy to moderate damage (red at ~100m from detonation) and moderate to light (yellow).

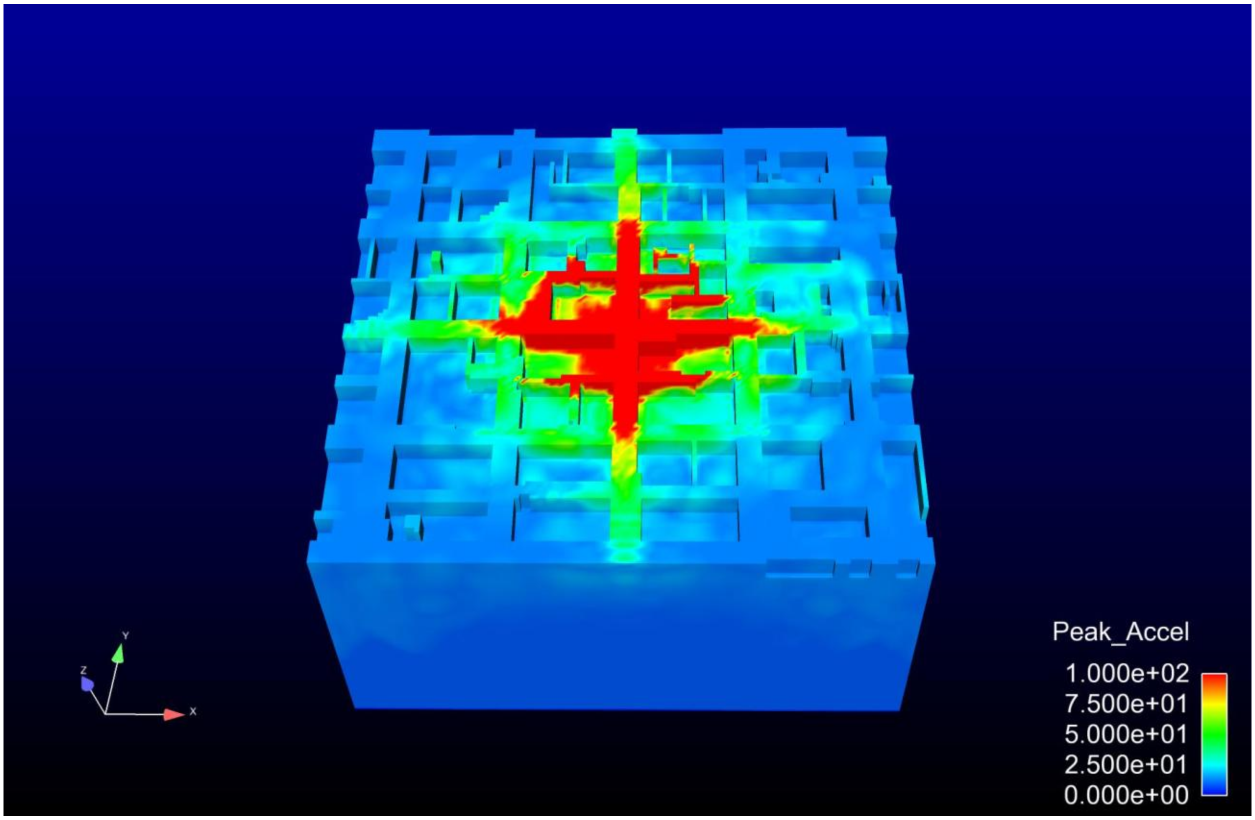


Figure 24. Peak accelerations experienced over the total time of the simulation (.1s). The urban underground canyon effect is shown in this picture.

Conclusions

The simulations in this report support the urban canyon effect for the below ground basement environment similar to the above ground air blast situation. Energy is channeled down the line of site streets which is exactly as seen in the above ground blast environment. Shock wave levels do not fall off as rapidly with distance from the detonation point as they do in an unobstructed simulation but there is no indication of enhancement due to reflections from the basements. Mainly this makes the waveforms less uniform with a higher frequency content.

For the 1KT detonation and using the DTRA levels defined in section 1, the heavy damage zone extends out to 50m (~100m for 10KT). The heavy to moderate zone is 50 to 100m (~100m to 200m for 10KT). For planning purposes it is recommended that this zone be viewed as having no operational infrastructure within it. Subway tunnels, while not operational, may be passable to human egress. Basements will in general be completely destroyed in the 50m radius which would imply that the buildings above would collapse. Of course, the air blast will have probably done the same to the above ground structure.

While showing in general the impacts, just as in the air blast calculations, coupling these results to a structure effects code would be very valuable in looking at more detailed effects. This simulation also used a constant depth of 20m for the basement structures primarily because of the absence of any other available information. It would be important to redo the simulation with more accurate representations of the real basement geometry in the vicinity of the detonation.

The 2D simulations point out the importance of including the local layering of materials under the city streets. This material is typically modified by various infrastructure projects and makes a significant effect on the transmission of the shock both down the streets and into the basement structures themselves.

These calculations also show that the source region from a seismic perspective would be very complicated and not necessary represented well as a spherical symmetric source.

References

1) **Lt.Col. H. Marcinowski, DTRA/CXSS , "IGVN Phase I : A Report Detailing Improvements to the Calculation of the Groundshock Vulnerability Number", Contract DTRA02-03-D-002, September 26, 2006.**
2) **Jon Rodgers, SNL, March, 2012, private communication**