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Computational Methods for Predicting the Response of Critical As-Built Infrastructure to Dynamic Loads (Architectural Surety)

D. S. Preece, J. R. Weatherby, S. W. Attaway, J. W. Swegle, R. V. Matalucci

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Computational Methods for Predicting the Response of Critical As-Built Infrastructure to Dynamic Loads (Architectural Surety)

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Abstract

Coupled blast-structural computational simulations using supercomputer capabilities will significantly advance the understanding of how complex structures respond under dynamic loads caused by explosives and earthquakes, an understanding with application to the surety of both federal and nonfederal buildings. Simulation of the effects of explosives on structures is a challenge because the explosive response can best be simulated using Eulerian computational techniques and structural behavior is best modeled using Lagrangian methods. Due to the different methodologies of the two computational techniques and code architecture requirements, they are usually implemented in different computer programs. Explosive and structure modeling in two different codes make it difficult or next to impossible to do coupled explosive/structure interaction simulations.

Sandia National Laboratories has developed two techniques for solving this problem. The first is called Smoothed Particle Hydrodynamics (SPH), a relatively new gridless method comparable to Eulerian, that is especially suited for treating liquids and

gases such as those produced by an explosive. The SPH capability has been fully implemented into the transient dynamics finite element (Lagrangian) codes PRONTO-2D and -3D. A PRONTO-3D/SPH simulation of the effect of a blast on a protective-wall barrier is presented in this paper.

The second technique employed at Sandia National Laboratories uses a relatively new code called ALEGRA which is an ALE (Arbitrary Lagrangian-Eulerian) wave code with specific emphais on large deformation and shock propagation. ALEGRA is capabile of solving many shock-wave physics problems but it is especially suited for modeling problems involving the interaction of decoupled explosives with structures. In this study, ALEGRA has been employed in modeling a decoupled explosive in a tunnel with the explosive and surrounding air treated with Eulerian computational techniques and the tunnel liner and surrounding soil treated with Lagrangian computational techniques.

Acknowledgment

The authors gratefully acknowledge the contribution of the team that performed the successful centrifuge experiment on a decoupled explosive in a tunnel. That team consisted of T. K. Blanchat, 6423; N. T. Davie, 9761; T. C. Togami, 9761; J. J. Calderone, 9761; R. A. Benham, 1553; B. D. Duggins, 1553; and D. E. Wackerbarth, 1553.

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1. Introduction

The new and emerging threats to the infrastructure faced by today's engineering design and facility management community demand solutions that are innovative and increasingly based on engineering science and risk management approaches. There is a growing awareness of public vulnerability in the wake of bombings at the World Trade Center, the Oklahoma City Federal Building, and the Khobar Towers military barracks in Saudi Arabia; global civil and ethnic unrest; criminal violence and political terrorism; recent devastating natural disasters; and other indicators of a rapidly transforming social world. This awareness leads to increased expectations by the public and more demanding responsibilities for the professional involved in design, engineering, and construction of public facilities. The destruction that follows such natural disasters as hurricanes, tornadoes, floods, fires, and earthquakes underscores the need for enhanced structural safety, security, and reliability to protect the public from potential injuries, death, and heavy property losses.

A multidisciplinary Architectural Surety Program has been developed at Sandia National Laboratories to address the application of safety, security, and reliability concepts and technology products to the many critical national issues involved in the area of multihazard mitigation. One of these applicable technology products is the modeling and simulation of building performance exposed to abnormal and malevolent environments. Computer simulation capabilities are the necessary and appropriate technologies to evaluate the response of complex structures, such as multistory buildings, when subjected to the variety of dynamic loads resulting from blast effects of explosive attacks or ground motions from earthquakes. To provide an adequate model simulation capability, it is necessary to modify as required, verify with actual data, and finally apply available coupled hydrocodes and structural dynamics codes to the analysis and design of federal buildings and facility systems that are or will be exposed to these abnormal and malevolent environments.

Through internal resources within the Laboratory Directed Research and Development (LDRD) Program, an Architectural Surety development effort was initiated and pursued to couple existing hydrocodes with existing structural dynamics codes. This effort was planned to evaluate the predictive capability using generic structures and typical explosive loads. After validating the coupled codes using test data, this predictive capability will assist with improved designs of new complex structures, give support to vulnerability assessment studies, guide the evaluation of alternative retrofits, and assist in the selection of the most cost-effective mitigation measures (such as stand-off distance, barrier walls, or other defensive techniques). The work to date provides positive evidence that the coupled codes are operational in the supercomputer at Sandia National

Laboratories. The next step is to perform a series of validation procedures using actual multistory structural test configurations and blast response data from a well-planned instrumentation system.

The U.S. Department of Energy has invested significant resources in the development of advanced computational mechanics codes and has performed research to understand phenomena and interactions between the transient dynamic response of structures and fluid-like materials. The Accelerated Strategic Computing Initiative (ASCI) program, with its emphasis on teraflops computers and parallel implementation of computer tools, has permitted the extension of this technology to high-fidelity, three-dimensional structural configurations. These new modeling and simulation techniques can provide a significant amount of information to make critical decisions about the impact of different threat levels, the effects of a variety of natural disasters, and the required enhancements to structures and facilities for life-safety concerns. The goal is to evaluate complex explosive interactions of catastrophic dynamic loads on structures. The work completed has addressed a significant portion of the previously recognized deficiencies. Completion and validation of the coupled code will provide a valuable tool to be used for architectural and infrastructure surety.

Work on two different corporate LDRDs is documented in this report. The first, sponsored through Division 5000 titled *Computational Methods for Predicting the Response of Critical As-Built Infrastructure to Dynamic Loads (Architectural Surety)*, the same title as this report. This LDRD sought to demonstrate the computational mechanics tools currently available at Sandia National Laboratories that can be adapted to modeling explosive/structure interaction. The second LDRD, sponsored through Division 9000 is titled *Development of Explosive Event Scale Model Testing Capability at Sandia's Large Scale Centrifuge Facility*. This LDRD sought to bring experimental and computational mechanics personnel together to address an issue that would be of national interest from an Architectural Surety perspective. A portion of that work is presented in this report because it is applicable to the scope of this LDRD. The latter LDRD is documented in much more detail in Blanchat et al. 1998.

2. Solid Wall Blast Simulation Using Smoothed Particle Hydrodynamics

Figure 1 illustrates a three-dimensional finite element model of a wall that will be subjected to an explosive loading. The wall is 1 ft thick and 13 ft high. The base is unattached to the ground beneath. Elastic concrete material properties are used for the wall and the ground with no allowance for damage or breakage in this calculation. Smoothed Particle Hydrodynamics (SPH) elements, represented by spheres, are shown in Figure 2 with the inner block modeling the explosive and the outer block serving as a buffer/transition zone between the explosive and the air. A JWL (Jones, Wilkins, Lee) equation-of-state is employed to model the explosive which is assumed to be 15352 lb of ANFO, separated from the wall by a six-ft gap. The air is modeled as an ideal gas. Figure 3 illustrates the SPH elements used to model the air between the explosive and the wall. Detonation of the explosive is modeled with a controlled burn based on the detonation velocity and point of initiation. Figure 4 shows the detonation of the explosive with its resulting pressure (psi) expansion and impact on the wall. Contact resolution between the SPH and finite elements results in a calculated explosive loading of the ground and wall. This loading results in the pressure (psi) pulse in the ground and wall as shown in Figure 5. The pressure applied to the wall causes the velocity (in./s) distribution illustrated in Figure 6. The pressure also produces a displacement (in.) of the wall at 3 ms, as displayed in Figure 7. The displacement of the closest corner of the wall (Figure 7) from the top to the bottom is given in Figure 8 for a number of different times, up to 3 ms. It is obvious from Figures 5 through 8 that the loading on this wall is concentrated on the lower right corner and that this corner will break off and move at high velocity. The remaining portion of the wall will move with significant velocity.

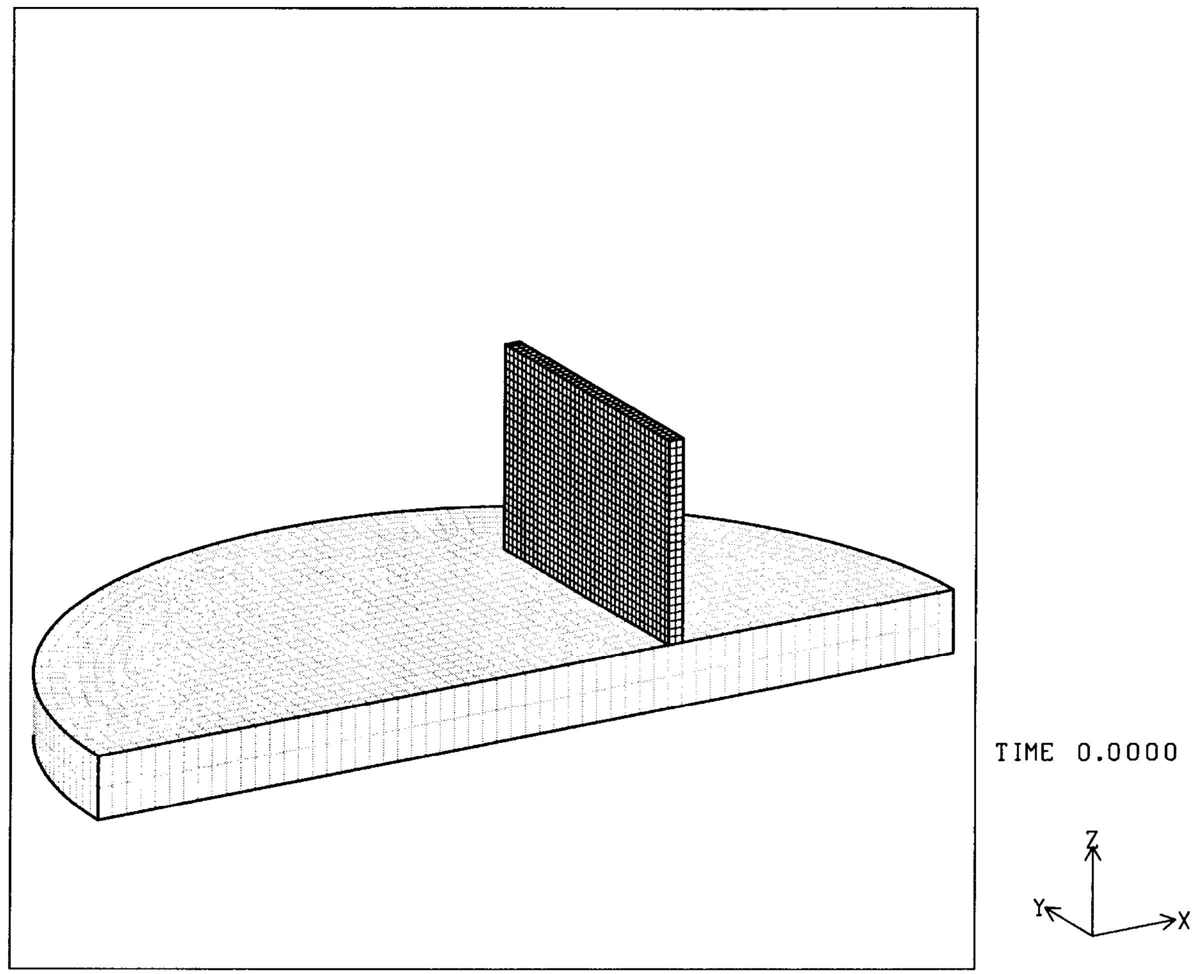

Figure 1. Wall and ground to be subjected to blast loading.

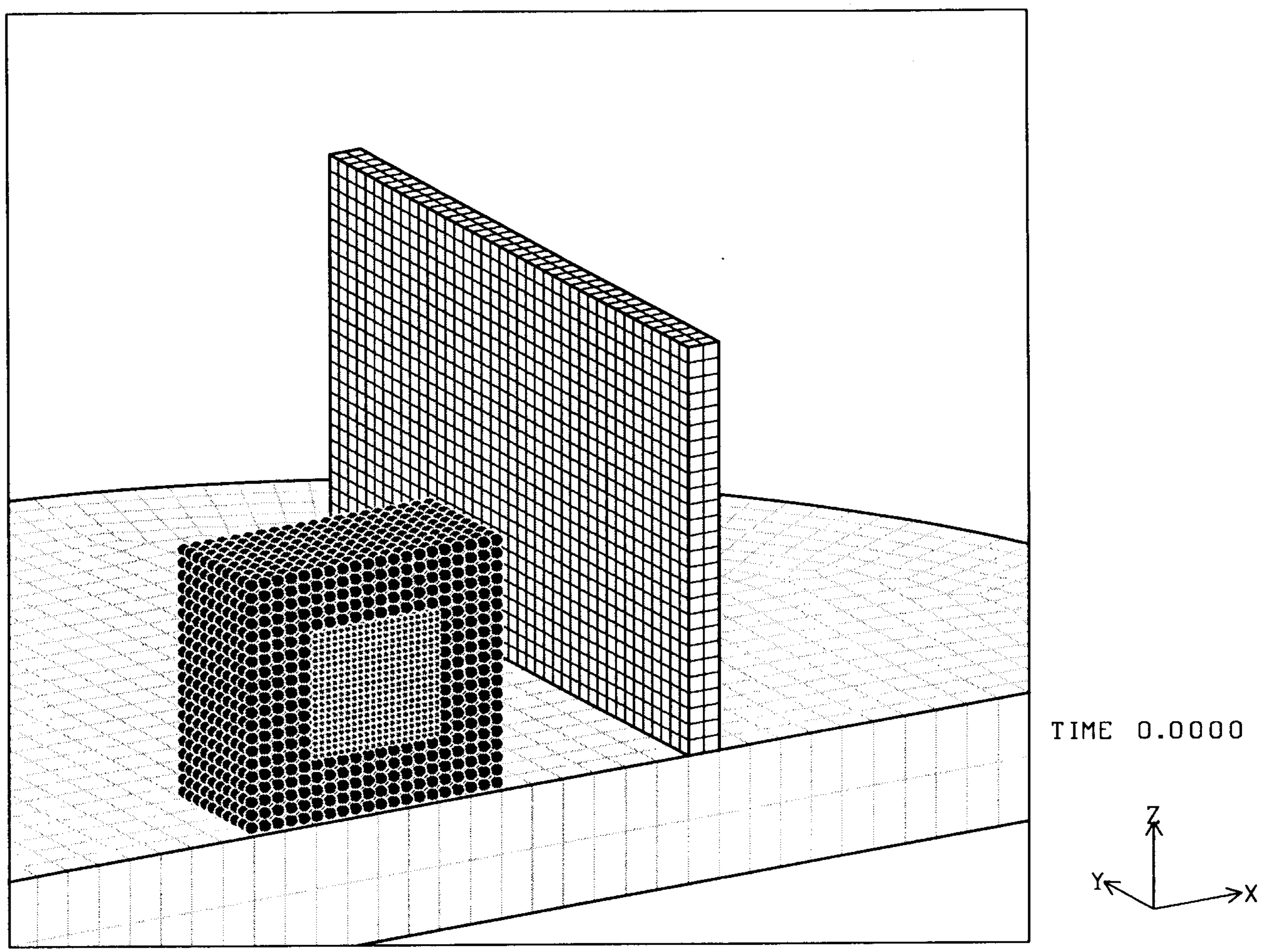

Figure 2. Explosive and buffer zone SPH elements with wall and ground.

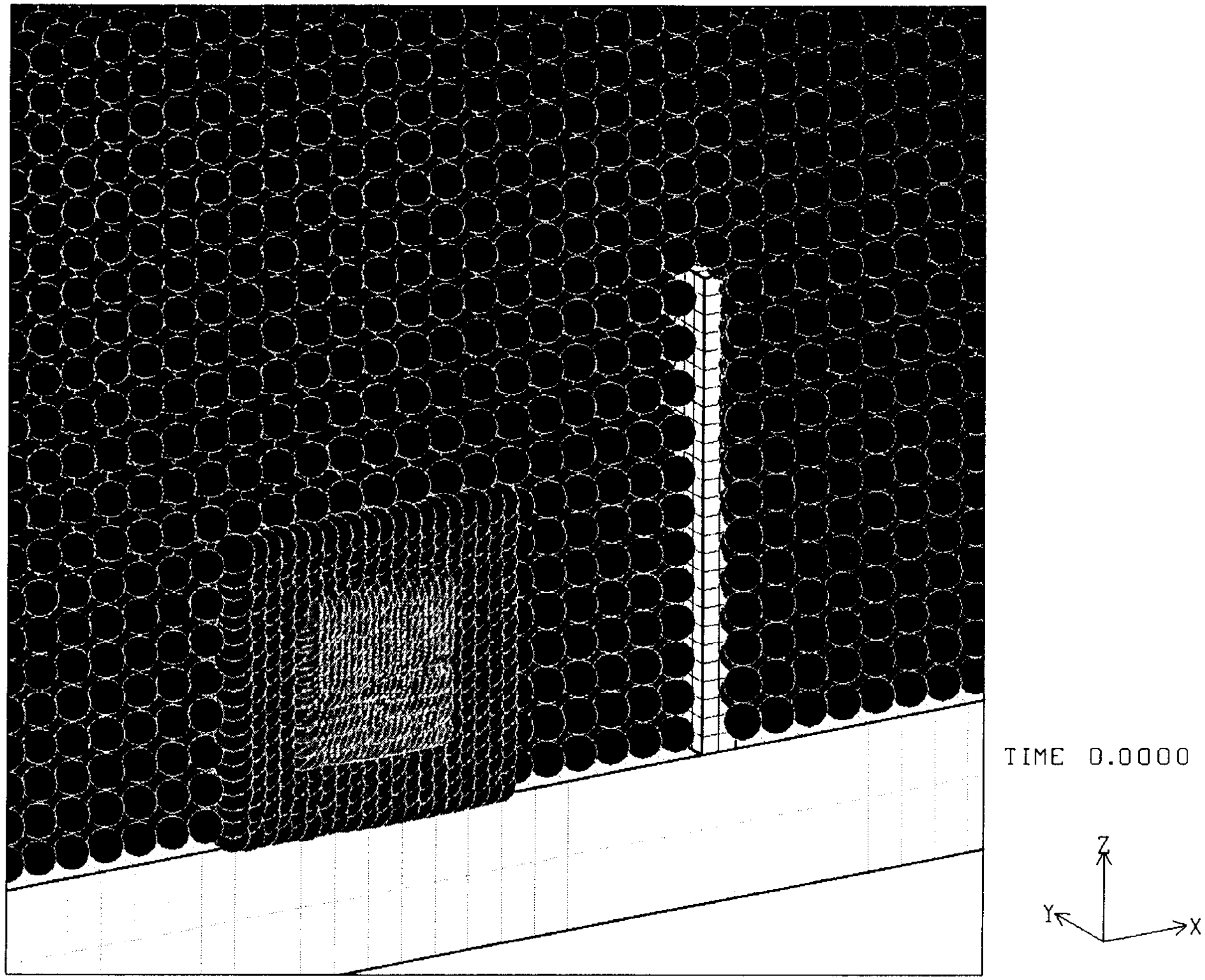

Figure 3. Explosive, buffer zone, and air SPH particles with wall and ground

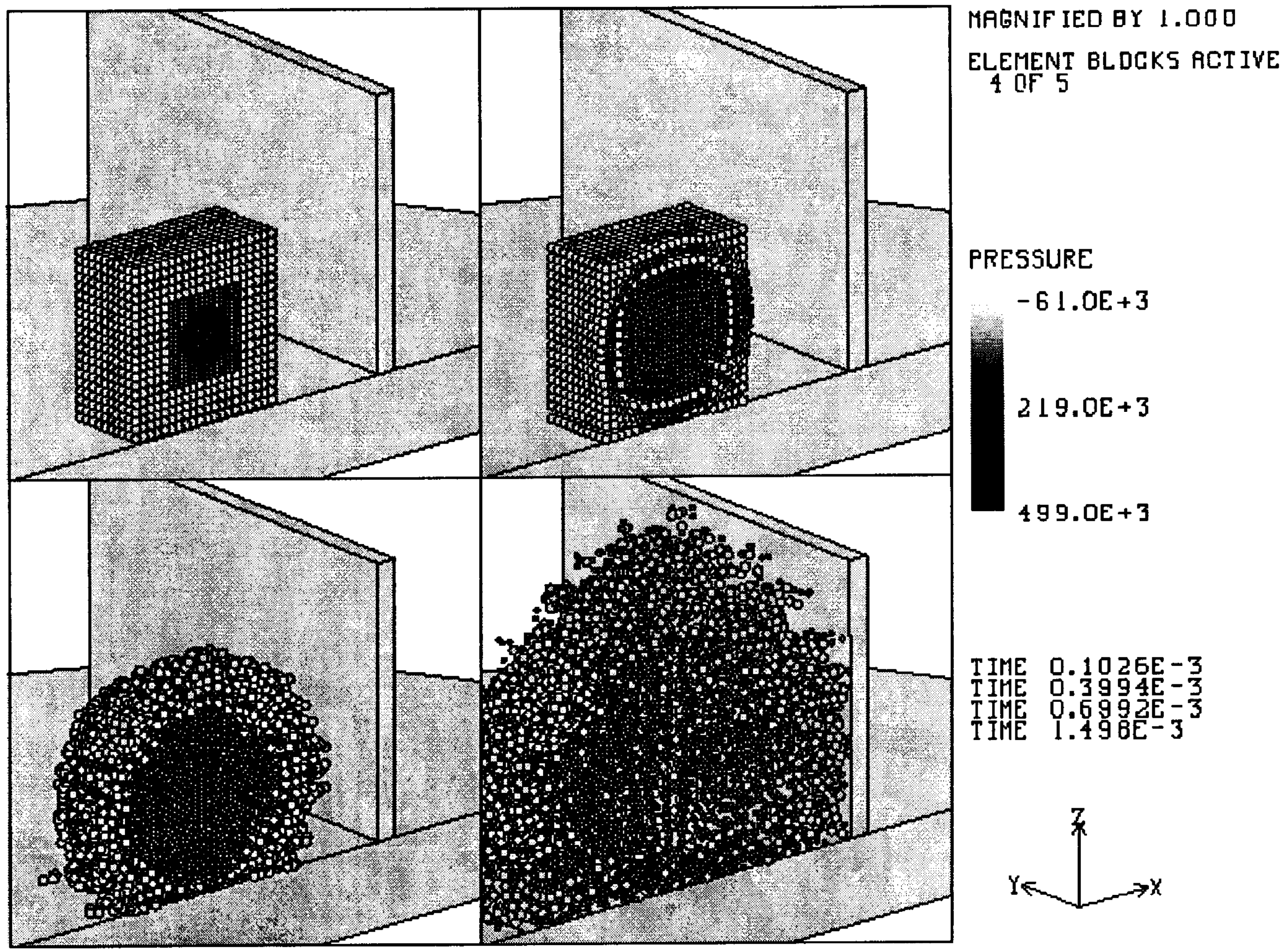

Figure 4. Pressure (psi) in SPH elements along with expansion and contact with wall. Air SPH elements withheld from display.

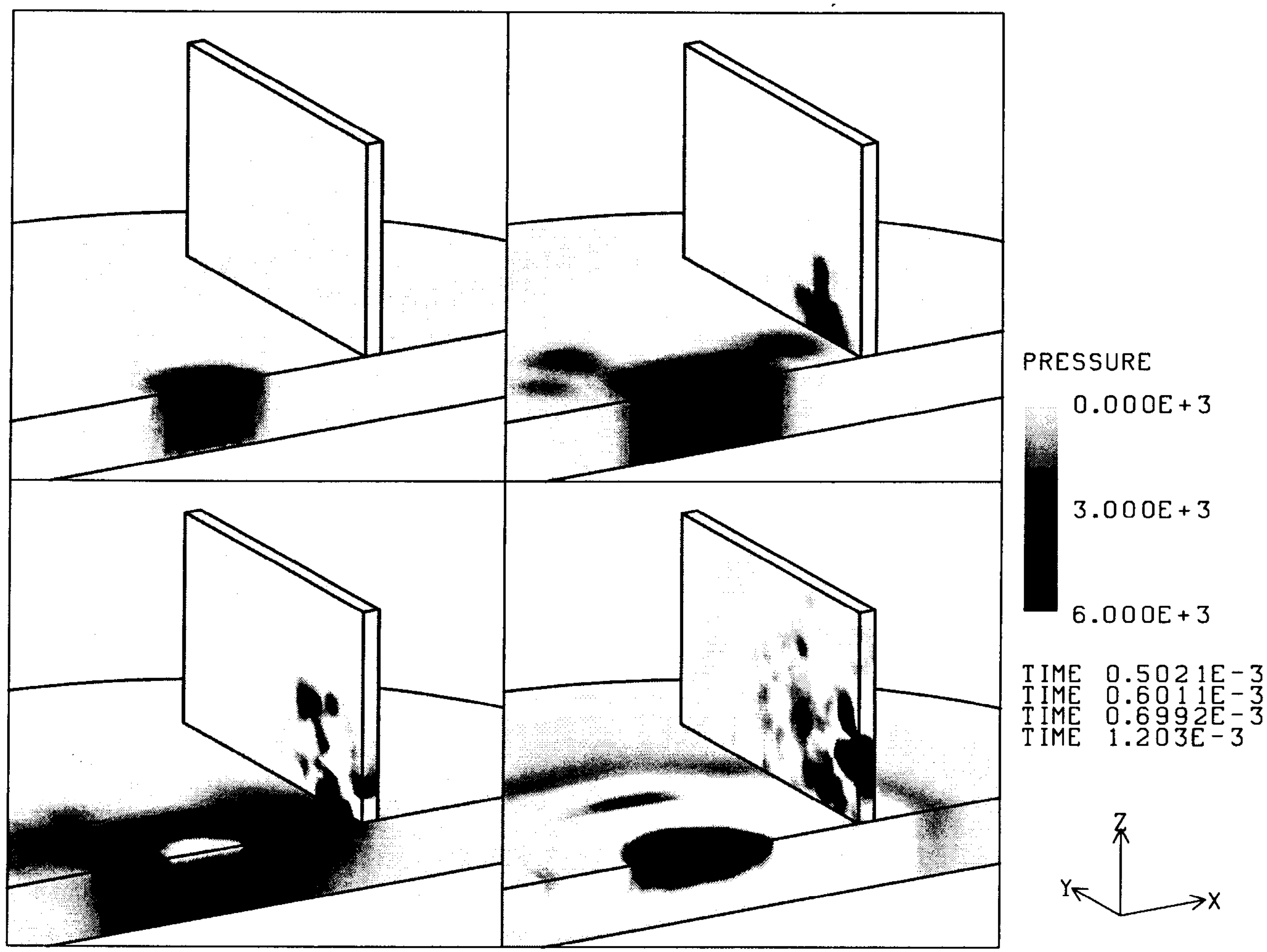

Figure 5. Pressure (psi) in the ground and wall induced by the explosive and air SPH particles.

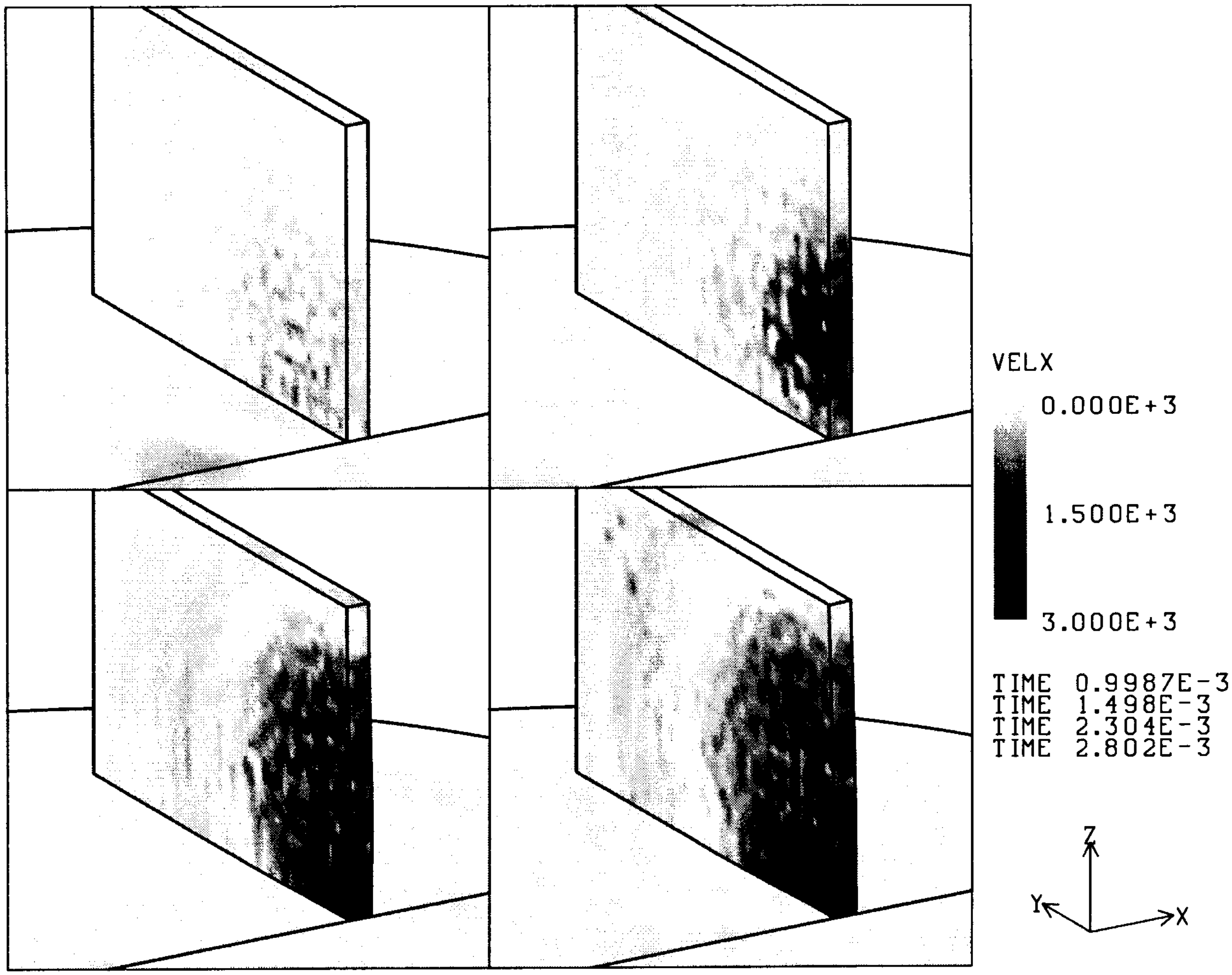

Figure 6. Velocity (in./s) of wall perpendicular to wall induced by pressure loading.

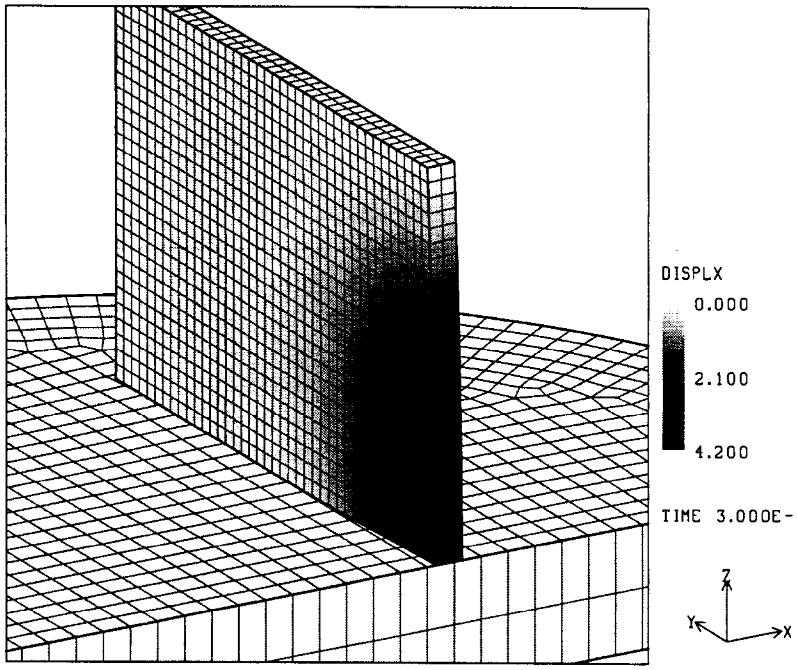

Figure 7. Wall displacement (in.) at 3.0 ms induced by pressure on wall.

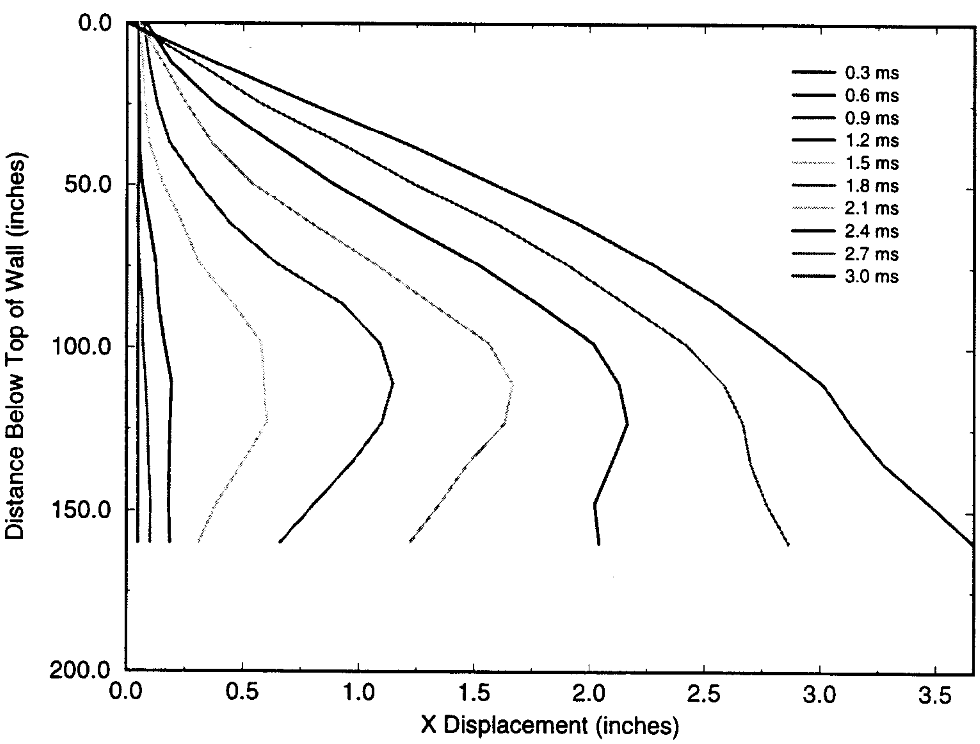

Figure 8. Displacement perpendicular to wall from the top to the bottom of the wall along the closest corner shown in Fig. 7. Lines representing increasing time, from 0 to 3 ms, starting on the left.

3. Block Wall Blast Simulation Using Smoothed Particle Hydrodynamics

Many structures of interest in Architectural Surety have walls constructed of cement-block or brick. The ability to analyze structures with these elements is of great interest. A calculation similar to that discussed in Section 2 has been performed that models a block wall rather than a solid wall, as shown in Figure 9. In this model each block contains a number of three-dimensional finite elements and thus is deformable. The exterior surface of each block is also a contact surface that can interact with every other block in the model to maintain geometric integrity as block collisions occur. The interaction of the blocks in this calculation is limited to friction. Modeling of mortar between blocks either as a tensile strength between blocks or explicitly with finite elements is a capability available in PRONTO-3D but is not utilized in this model. Figure 10 illustrates the explosive and explosive/air transition zone adjacent to the block wall. Figure 11 shows the detonation and expansion of the SPH particles used to model the explosive gases and the interaction of those gases with the block wall. The explosive dimensions, mass, equation-of-state, and location relative to the wall are identical to those employed in the solid wall model discussed earlier. Figures 12 and 13 illustrate the calculated response of the blocks to the explosive loading at 5.8 ms. The calculation was terminated at this point due to an error in the SPH particle contact algorithm. This error has since been corrected.

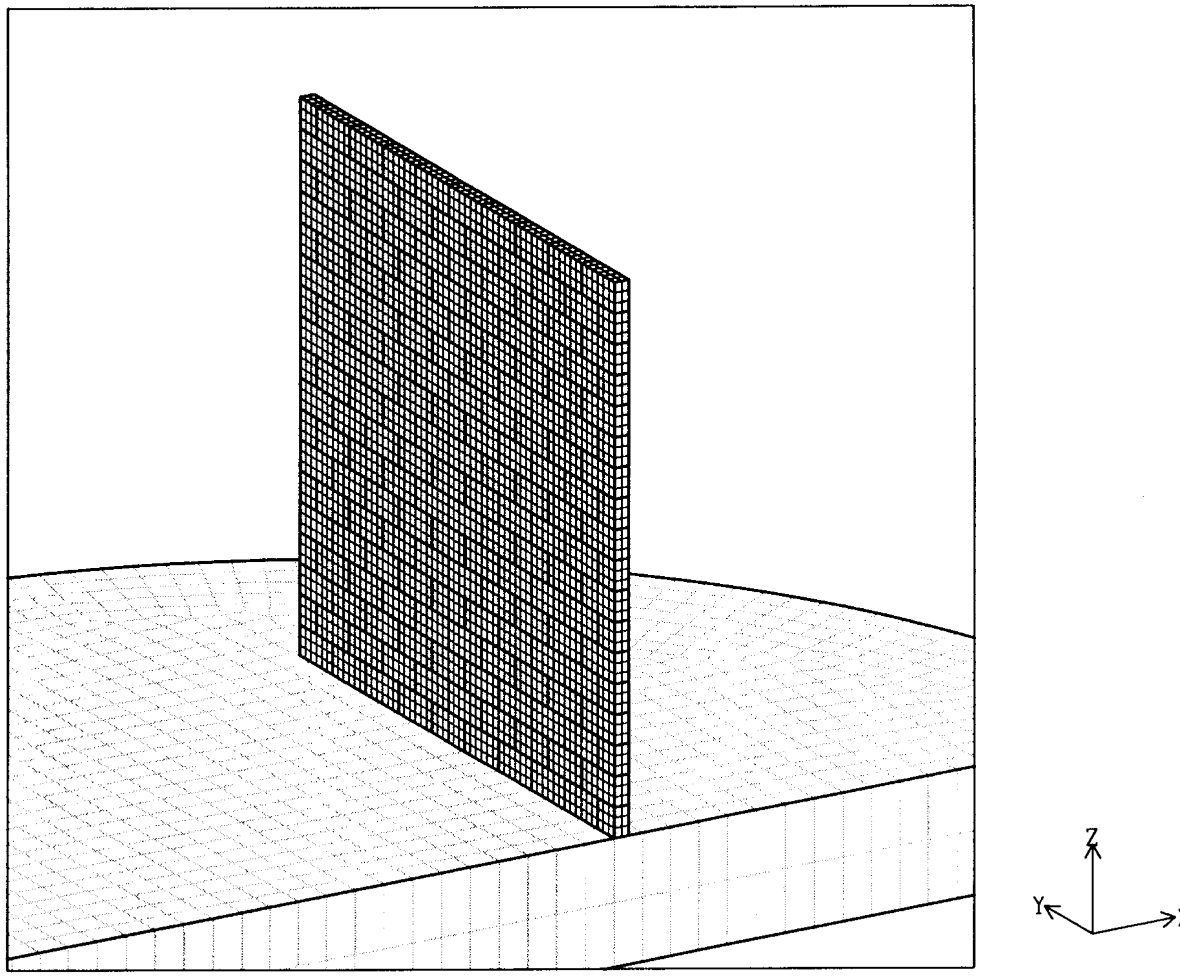

Figure 9. Block wall and ground to be subjected to blast loading

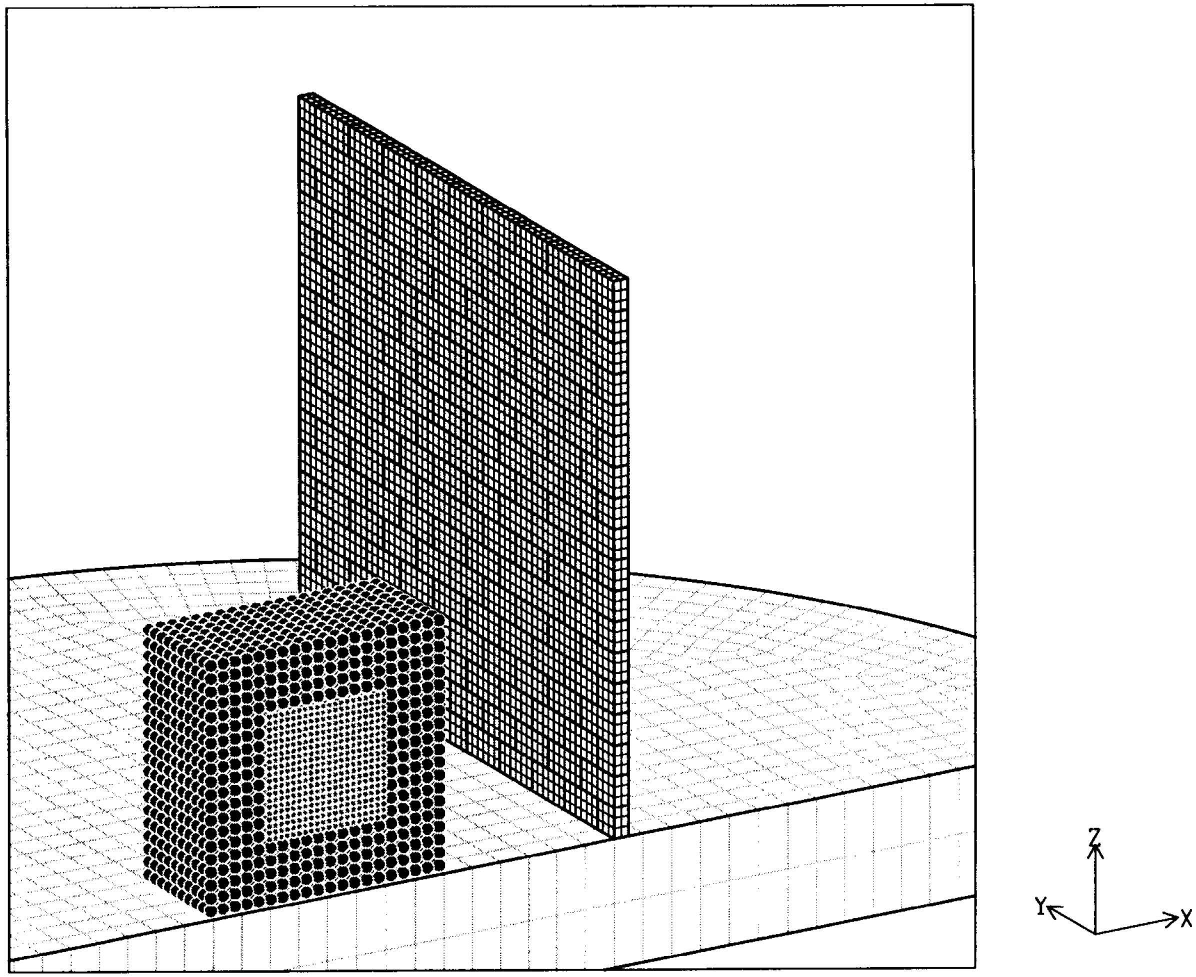

Figure 10. Explosive and buffer zone SPH elements with block wall and ground.

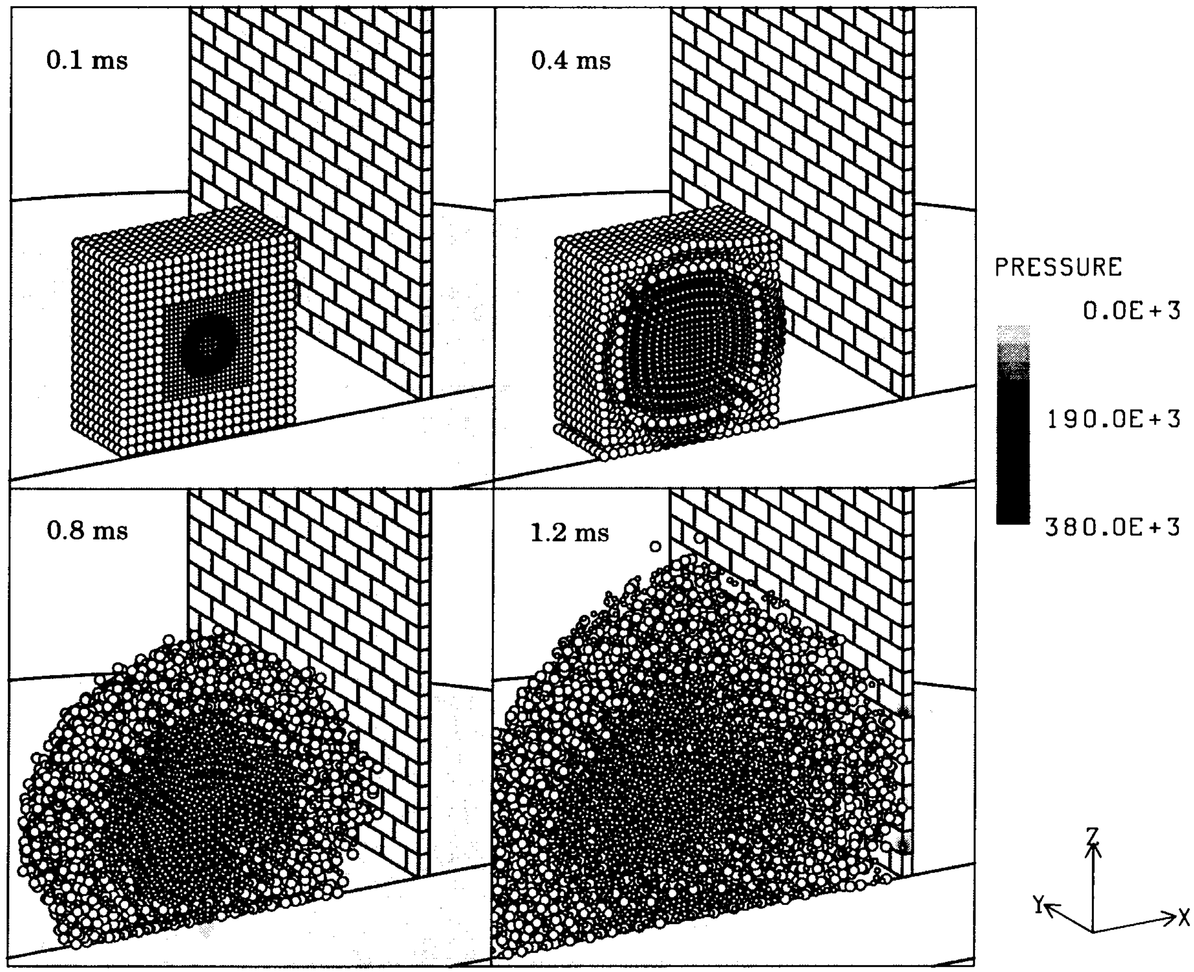

Figure 11. Pressure (psi) in SPH elements along with expansion and and contact with block wall. Air SPH elements withheld from display.

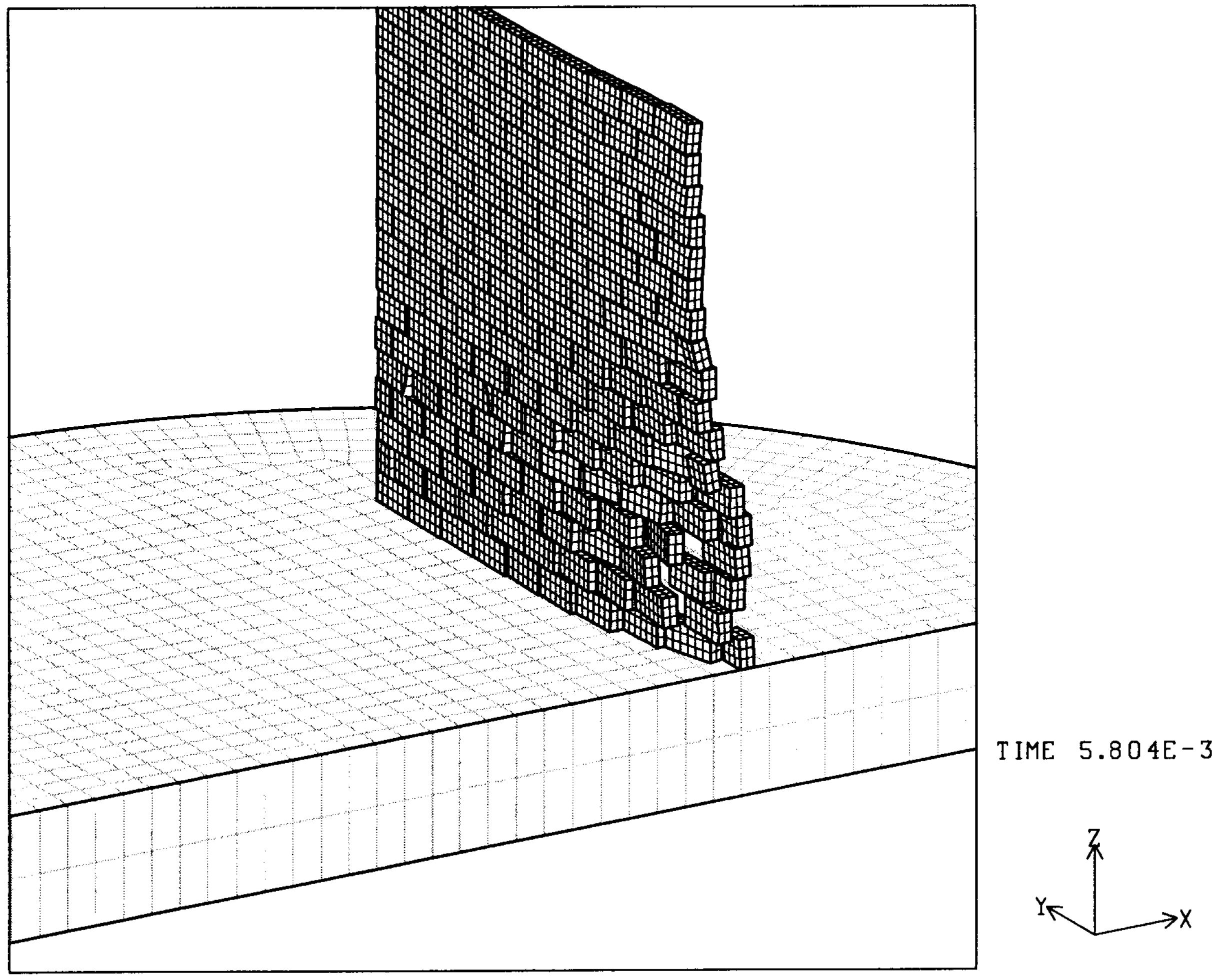

Figure 12. Block wall deformation and motion at 5.8 ms.

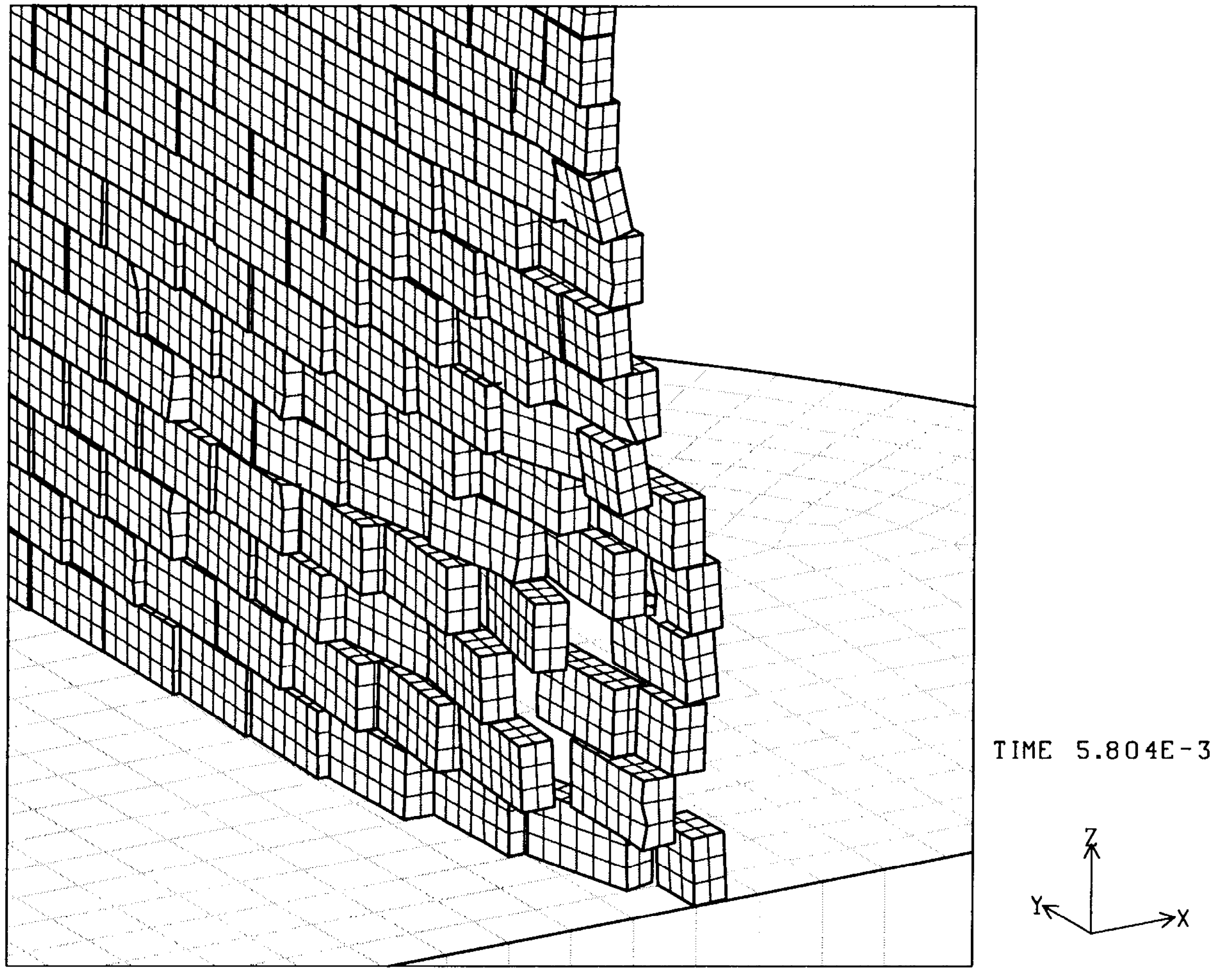

Figure 13. Zoom in on deformed block wall shown in Figure 12.

4.0 Design of Centrifuge Explosive Experiment Using Computer Simulations

4.1 LDRD Background

The LDRD, as originally written, proposed to perform gravity scaling of an explosive event in a steady-state acceleration environment available through centrifuge testing. Many different types of explosive events amenable to gravity scaling were available, including cratering; a scale model building with explosively induced; gravity driven progressive collapse; and tunnels in rock or soil subjected to decoupled explosive loading. After considerable discussion it was decided to focus on a decoupled explosion in a tunnel in an engineered soil. The engineered soil had been used in a previous study (Tieszen and Attaway 1996). This configuration was chosen because length scales directly with gravity on underground structures with regards to stress and deformation.

4.2 ALEGRA

The computer code ALEGRA was used in this study to design the size and thickness of the aluminum tunnel liner and the decoupled explosive charge inside the tunnel. ALEGRA is an arbitrary Lagrangian-Eulerian (ALE) wave code with specific emphasis on large distortion and shock propagation. (Budge et al. 1997a; Budge et al. 1997b).

4.3 Preliminary Calculations

Preliminary calculations were performed using a pseudo-one-dimensional ALEGRA model. This model treats the explosive, air, tunnel liner and soil as depicted in Figure 14. Computational cells or elements in this model are actually two-dimensional axisymmetric but the boundary conditions on the model constrain it to one-dimensional behavior such as that observed when a shock wave is transmitted lengthwise through a metal rod. A gravitational acceleration of 100 g in the negative x direction is applied to this model.

A JWL equation-of-state, with a programmed burn, was employed to model the PBX-9407 explosive detonation (Budge et al. 1997a). Parameters necessary to characterize the explosive behavior during detonation are given in Table 1.

A soil/compressible-foam constitutive model was used to model the engineered soil compacted around the aluminum pipe. The parameters pertinent to this material model are presented in Tables 2 and 3. Table 2 contains the single-value parameters associated with this model, and Table 3 shows the pressure versus volumetric strain relationship necessary for the model.

Table 1. JWL equation-of-state parameters for PBX-9407

Parameter	Value	Units
ϒ (reference density)	1.62	g/cm^3
A	5.73187E12	$dyne/cm^2$
B	1.4639E11	$dyne/cm^2$
C	1.20E10	$dyne/cm^2$
ω	0.32	
R_1	4.6	
R_2	1.4	
CJ pressure	2,65E11	$dyne/cm^2$
D (detonation velocity)	7.91E5	cm/s
CJ temperature	4962.0	^{o} Kelvin

Table 2. Soil and Crushable Foam Constitutive Model Parameters for Engineered Soil

Parameter	Value	Units
ϒ (initial density)	1.393	g/cm^3
K (bulk modulus)	2.0E8	$dyne/cm^2$
G (shear modulus)	640.0	$dyne/cm^2$
A_0	5.51E5	
A_1	0.95	
A_2	0.0	
Fracture Pressure	-1.0E3	$dyne/cm^2$

Table 3. Pressure Versus Volumetric Strain for Engineered Soil

Volumetric Strain (%)	**Pressure (dyne/cm^2)**
0.006	239240.0
0.02	478400.0
0.064	957600.0
0.114	1909800.0
0.2231	3495600.0
0.24	3826500.0
0.26	5743300.0
0.27	7653100.0
1.0	148580000.0
1.73	289506900.0

An elastic-perfectly-plastic constitutive model was employed to model the aluminum tube that served as the tunnel liner after the emplacement of the soil around the tube. The constitutive model parameters selected for aluminum are given in Table 4.

Table 4. Elastic-Perfectly-Plastic Constitutive Parameters for Aluminum Tube

Parameter	**Value**	**Units**
E (Youngs Modulus)	6.89E11	dyne/cm^2
μ (Poisson's ratio)	0.334	
Yield stress	2.76E9	dyne/cm^2
Hardening modulus	1.02E10	dyne/cm^2
Beta	1.0	

The final material behavior model necessary for this simulation is for the air that decouples the explosive from the tunnel liner. This was treated as an ideal gas with parameters given in Table 5.

Table 5: Ideal Gas Parameters for Air

Parameter	**Value**	**Units**
ρ_o (Reference density)	0.001225	g/cm^3
Υ	1.4	
T_0 (Reference temperature)	288.2	^{0} Kelvin
C_V	0.7178E4	

Variables that could be adjusted in this model included explosive radius, tunnel radius, and tunnel liner thickness. A tunnel diameter of 1.5 in. was chosen based on the general physical dimensions of the existing centrifuge swing-arm that constrained the size of the container holding the tunnel experiment. The container was sized to be a cube 2 ft on each side. The 2 ft depth with the tunnel in the center dictated one foot of soil above and below the tunnel. Experience indicated that the tunnel diameter should be approximately one-tenth the length of the soil surrounding it to control the influence of the upper (free) surface and lower (fixed) surface. The tunnel diameter was thus set at 1.5 in. The experimental configuration chosen is depicted in Figure 15 which shows the explosive, tunnel liner, and soil as designed.

A steady-state acceleration environment of 100 g on the centrifuge produces the same stresses and deformations in the soil and tunnel as would be observed in a model with all lengths multiplied by 100. This model thus simulates a 150 in. (12.5 ft., 3.81 m) diameter tunnel buried 100 ft. (30.48 m) deep.

With tunnel diameter and depth-of-burial already determined, the two variables that could be adjusted in the experiment were explosive diameter and tunnel liner thickness. Experience indicated that the diameter of the explosive would be the most important explosive parameter influencing its' effect on the tunnel liner. This was proven later by both the two-dimensional calculations and the experiment itself.

It was decided that the criteria for controlling the combination of explosive diameter and tunnel liner thickness should be measurable plastic deformation of the tunnel liner resulting from explosive detonation inside the tunnel. The tunnel liner thickness and explosive diameter were both constrained by the commercially available sizes. A number of simulations were performed with several combinations of explosive diameter and tunnel thickness using ALEGRA and the pseudo one-dimensional model.

The best combination arrived at was a tunnel liner thickness of 0.083 in. (0.2108 cm) and an explosive diameter of 0.1875 in. of PBX-9407. The length of the explosive was set at 3.75 in. (9.525 cm), which resulted in a total explosive weight of 2.75 g.

4.4 Detailed Two-Dimensional Simulations

All design parameters discussed above were employed in a more detailed two-dimensional axisymmetric model of the tunnel experiment on the centrifuge. A close-up of the two-dimensional axisymmetric ALE model is shown in Figure 16. In this model the explosive, aluminum and soil are located just as in the one-dimensional model of Figure 14. The material models for the explosive, air, aluminum, and soil used in the two-dimensional model are exactly the same as those given above for the pseudo- one-dimensional model. Detonation of the explosive is designated to occur along the line on the bottom of the explosive. This model also has a gravitational acceleration of 100 g in the negative x direction.

Pressure caused by the detonation of the explosive and the deformation of the aluminum liner from times 0.0 to 245 μs is shown in Figures 17 through 19. In Figures 17 and 18 the pressure corresponding to black has been set at 1.0E9 dynes/cm^2. Pressures greater than this value are also plotted as black. A number of very interesting phenomena can be observed in this series of figures. In Figure 17 at 5 μs the air is being pushed ahead of the explosive gas because of the large density difference between the two. By 8 μs the air has been compressed by the explosive gas against the aluminum liner and begins to rebound as illustrated at 12 and 14 μs. At 19 μs the air is reconverging in the center of the tube where the explosive was before detonation. Thus, the shock wave marking the separation between the air and explosive gas reverberates a number of times in the tube. The majority of the energy imparted to the tube resulting in plastic deformation is expended during the initial impact of the explosively induced shock wave on the aluminum tube. Plastic deformation of the tube can be seen starting as early as 8 μs. Transmission of the explosively induced shock wave through the tunnel liner and into the soil is observed in Figure 19 where the plotting pressure range has been significantly reduced to highlight lower pressures. The final predicted deformed shape of the tube is shown in Figure 20. The tube flare is the same length as the explosive and the outward displacement is constant indicating that the pseudo one-dimensional ALEGRA model used for the design of this experiment is an acceptable approach. The final outward displacement predicted by the one-dimensional model was 0.24 cm compared with 0.14 cm calculated from the two-dimensional model. A preliminary experiment was done wherein the explosive charge was detonated inside a bare tube wrapped with rubber. The outward displacement of the tube in this experiment was 0.15 cm. More details concerning this centrifuge experiment and the numerical analyses can be found in Blanchat et al (1998).

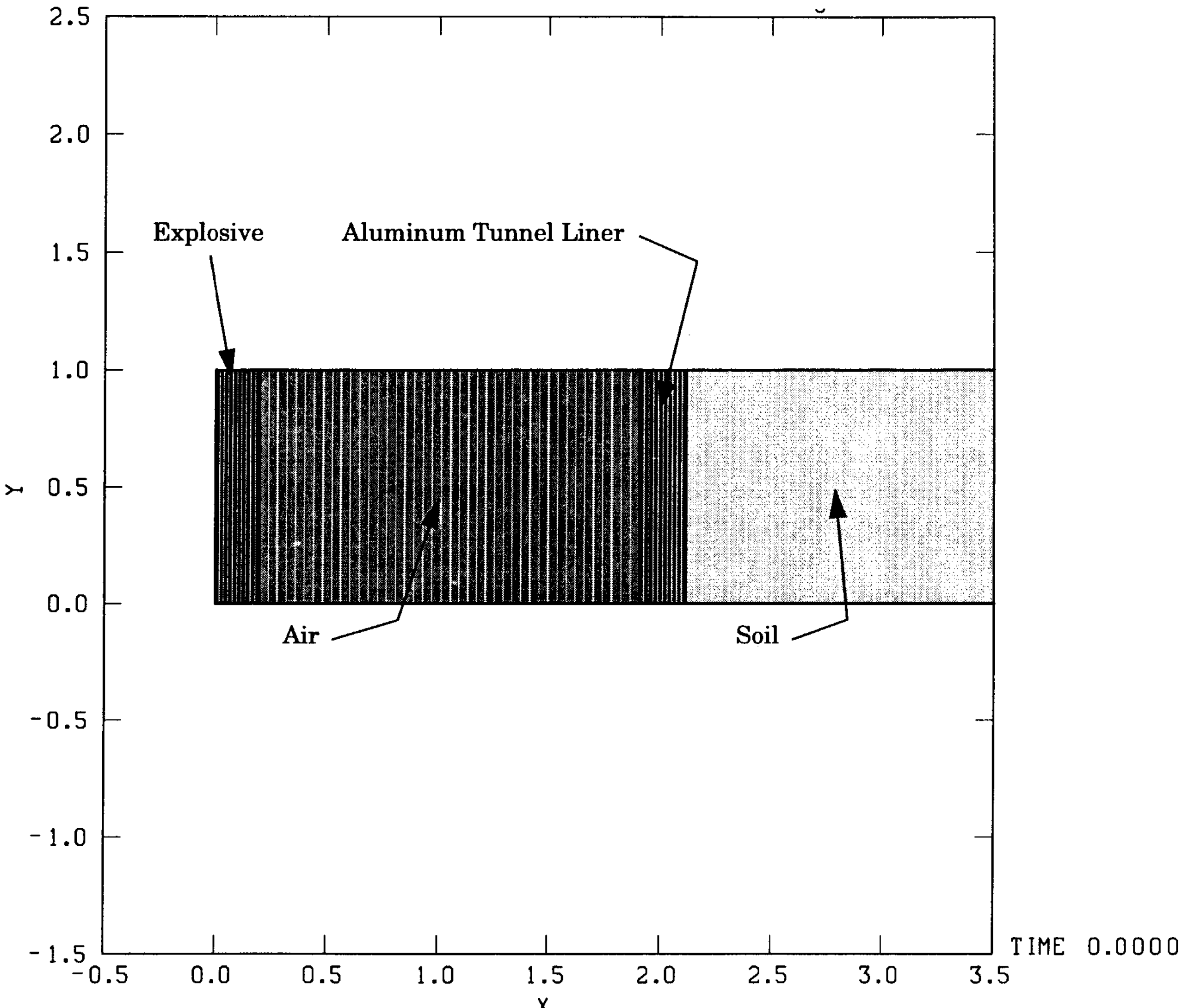

Figure 14. Pseudo-one-dimensional ALE model used to design the decoupled explosive tunnel experiment.

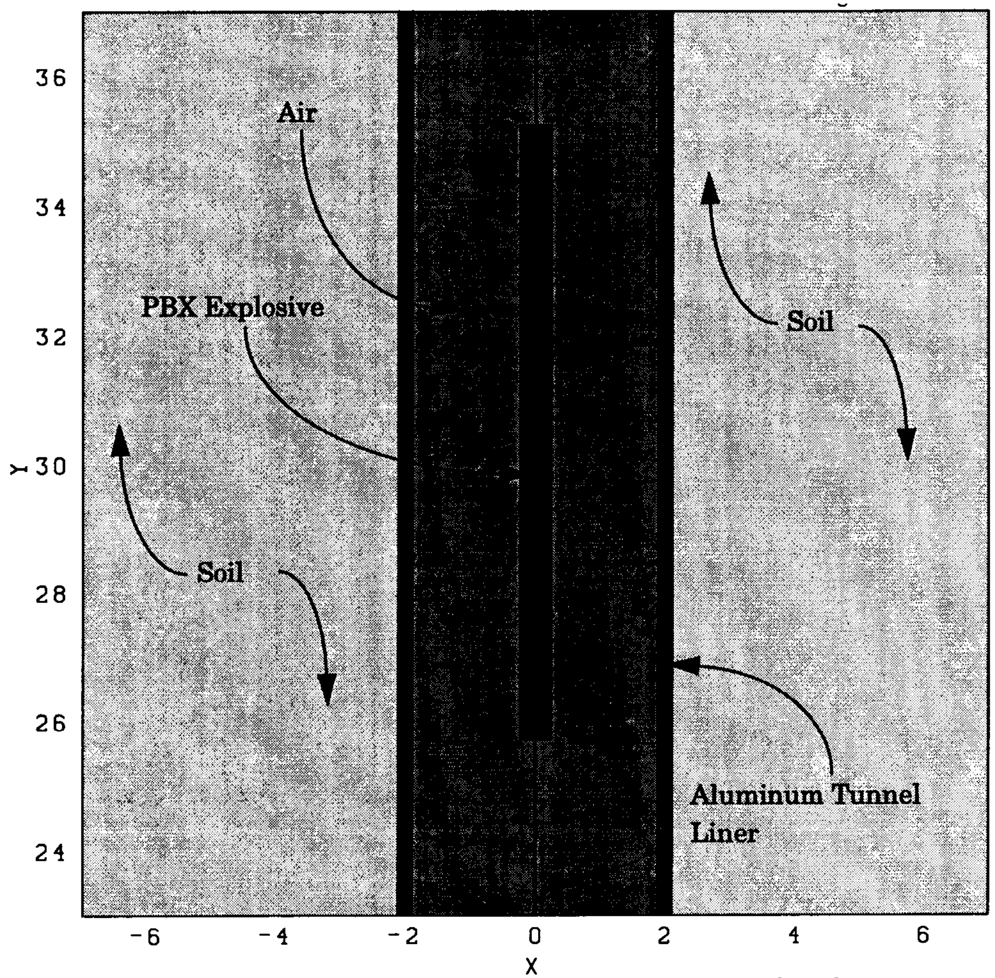

Figure 15. Two-dimensional ALE model used to predict the response o the model to a decoupled explosive in a tunnel.

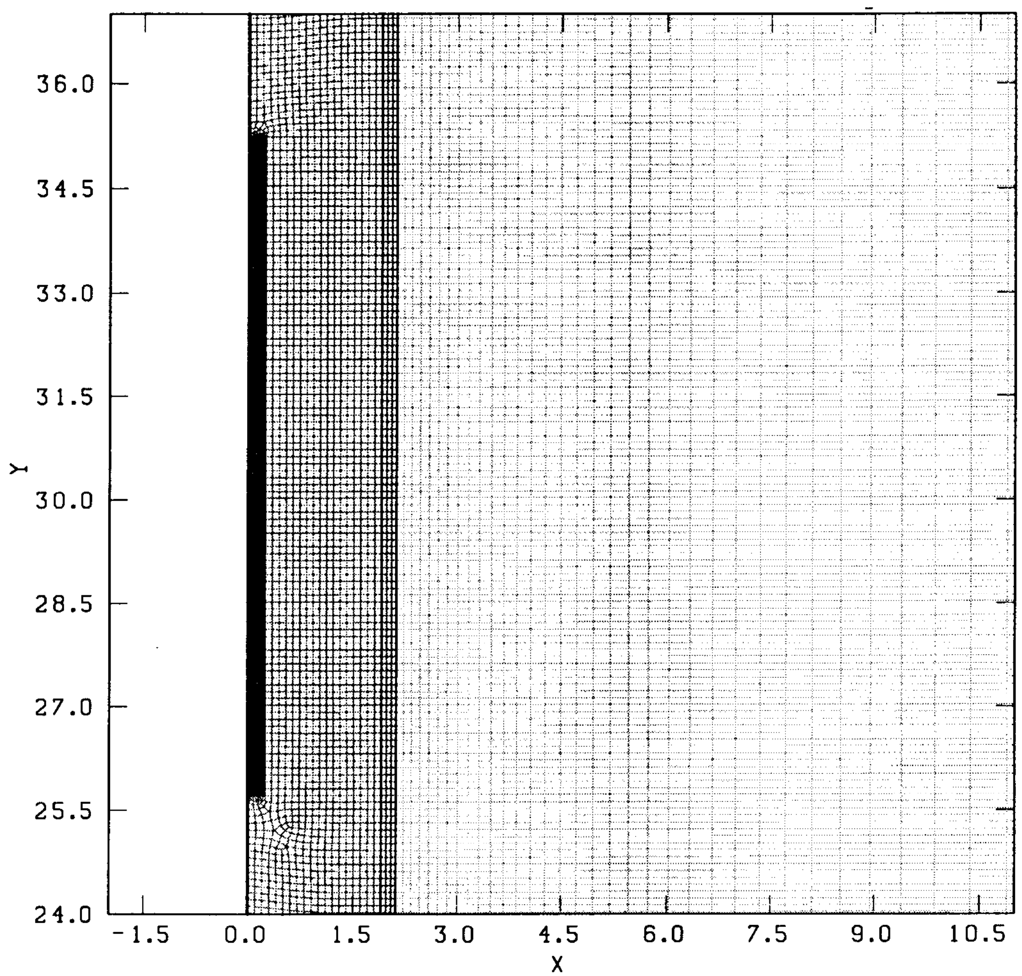

Figure 16. Two-Dimensional ALE model of explosive, air, aluminum, and soil

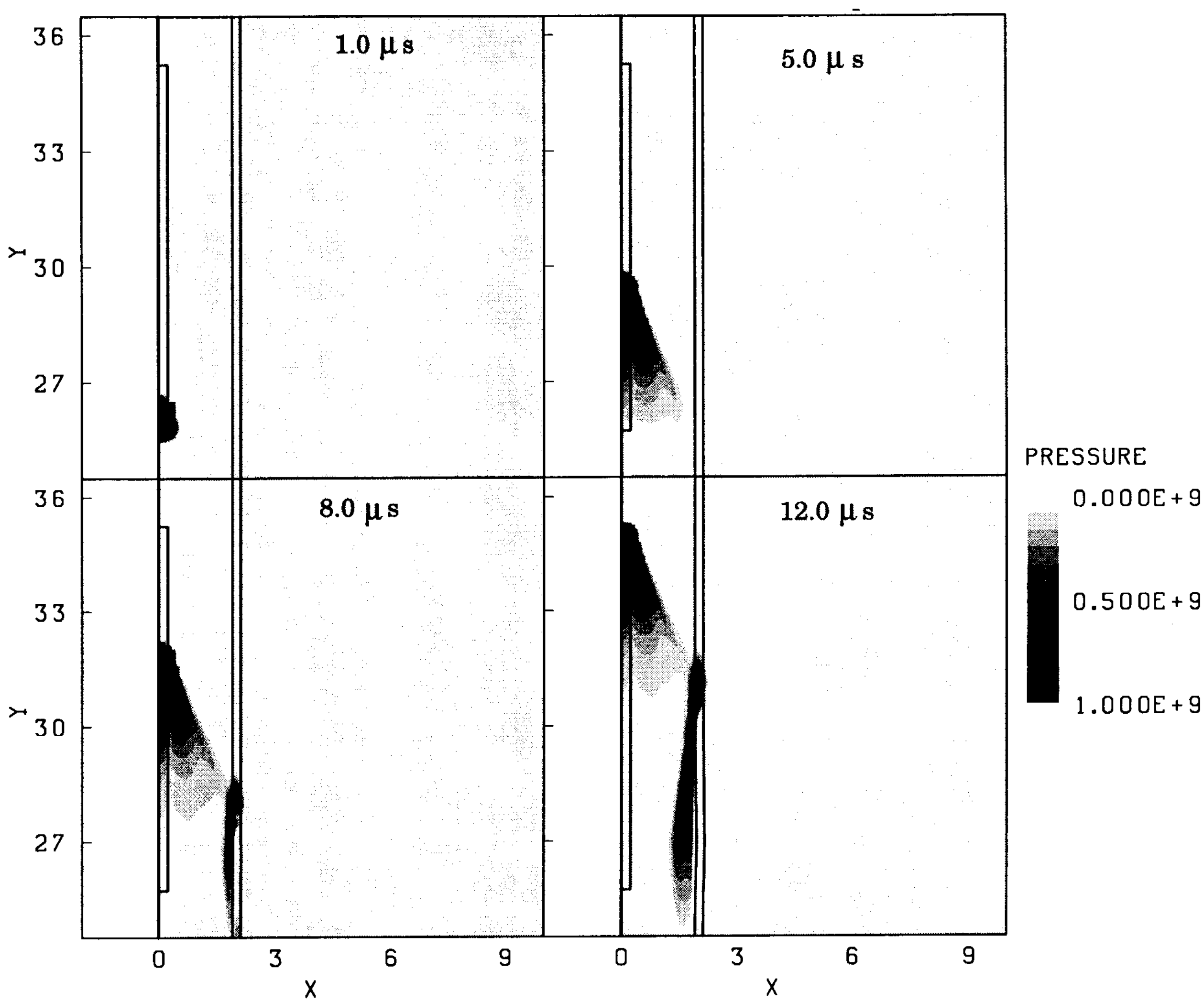

Figure 17. Pressure (Pa) induced by the explosive at 1.0, 5.0, 8.0, and 12 μs.

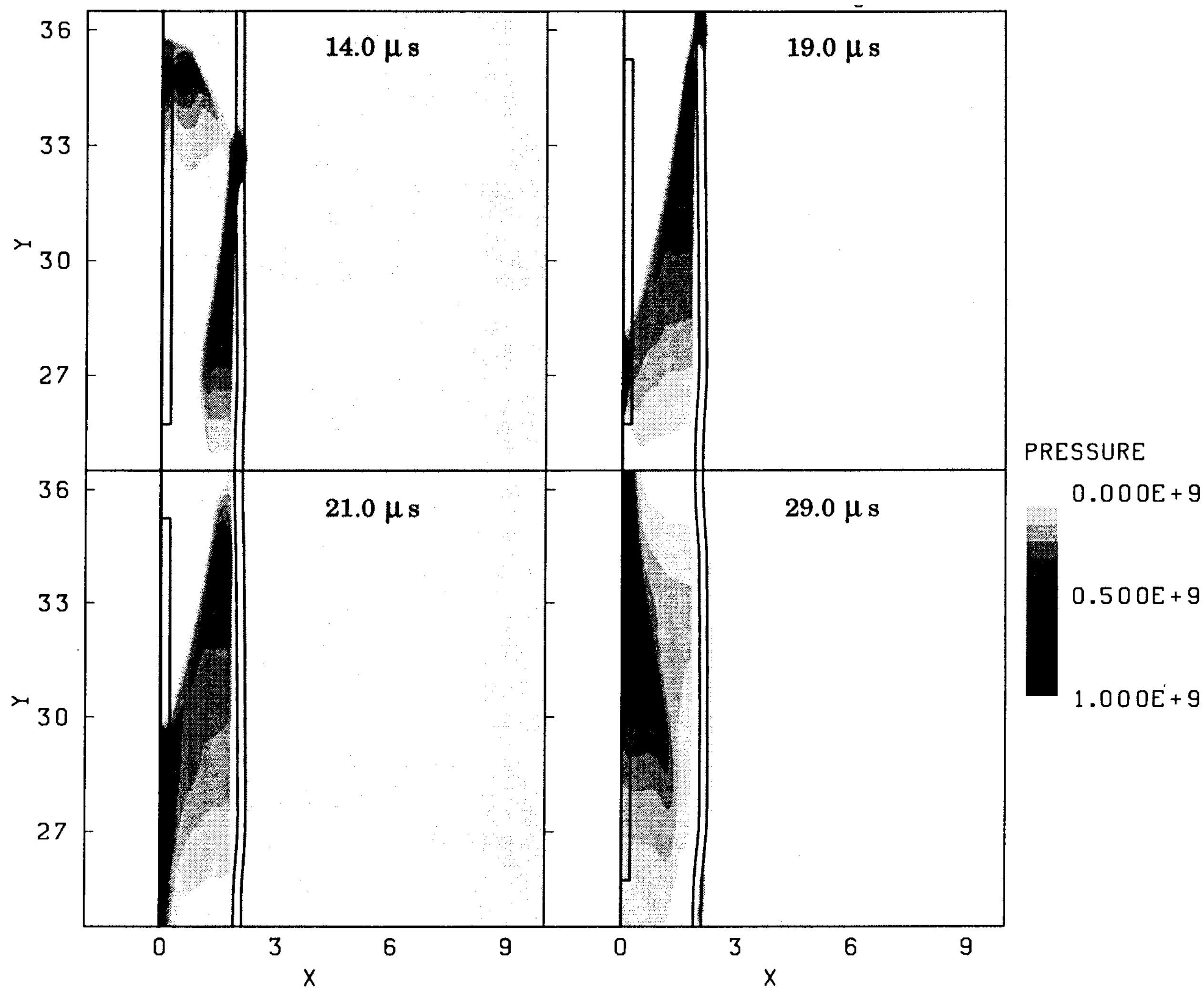

Figure 18. Pressure (Pa) induced by the explosive at 14, 19, 21 and 29 μs.

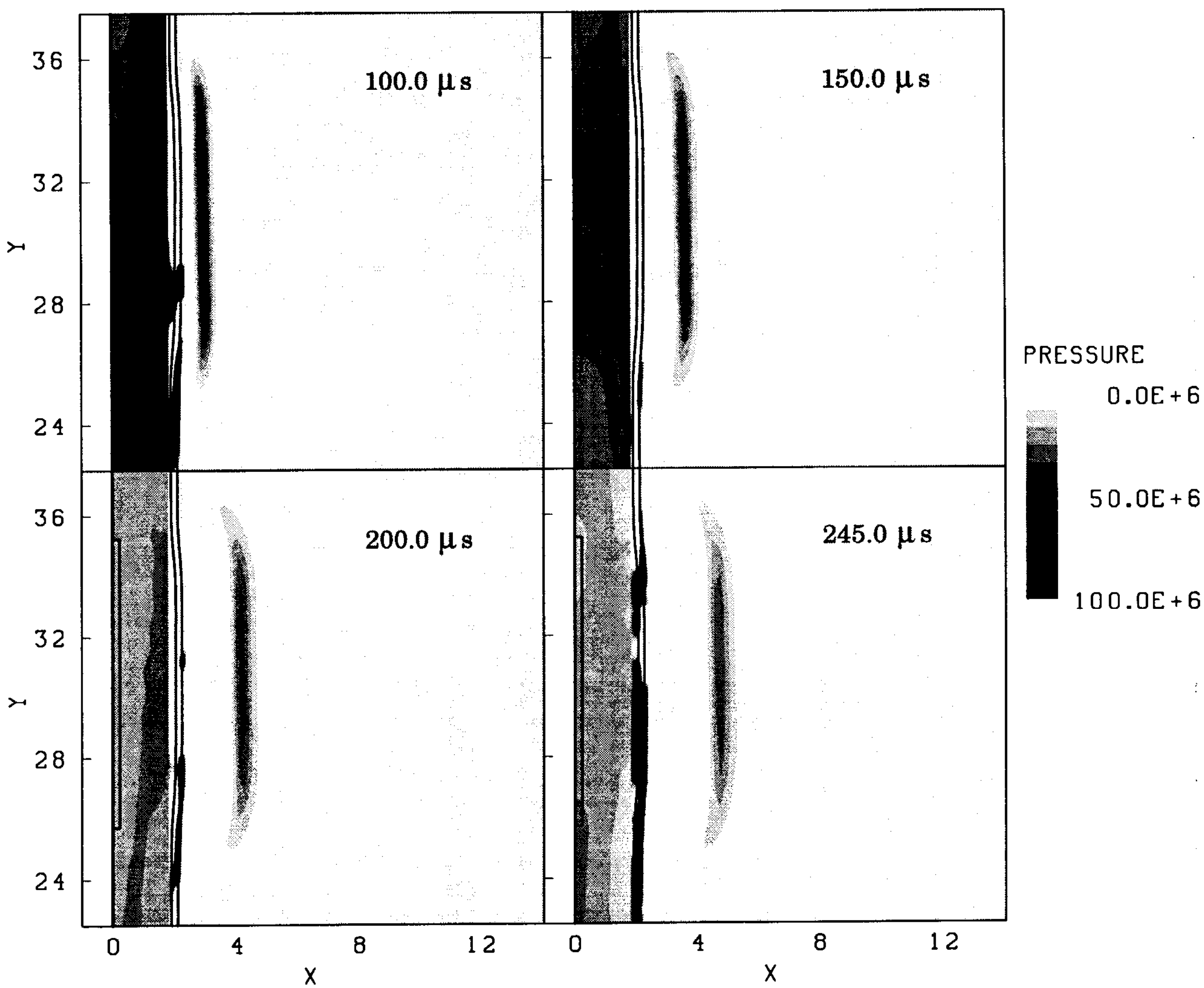

Figure 19. Pressure (Pa) induced by the explosive at 100, 150, 200, and 245 μs. Note the difference in the pressure range to highlight the shock wave moving outward through the soil.

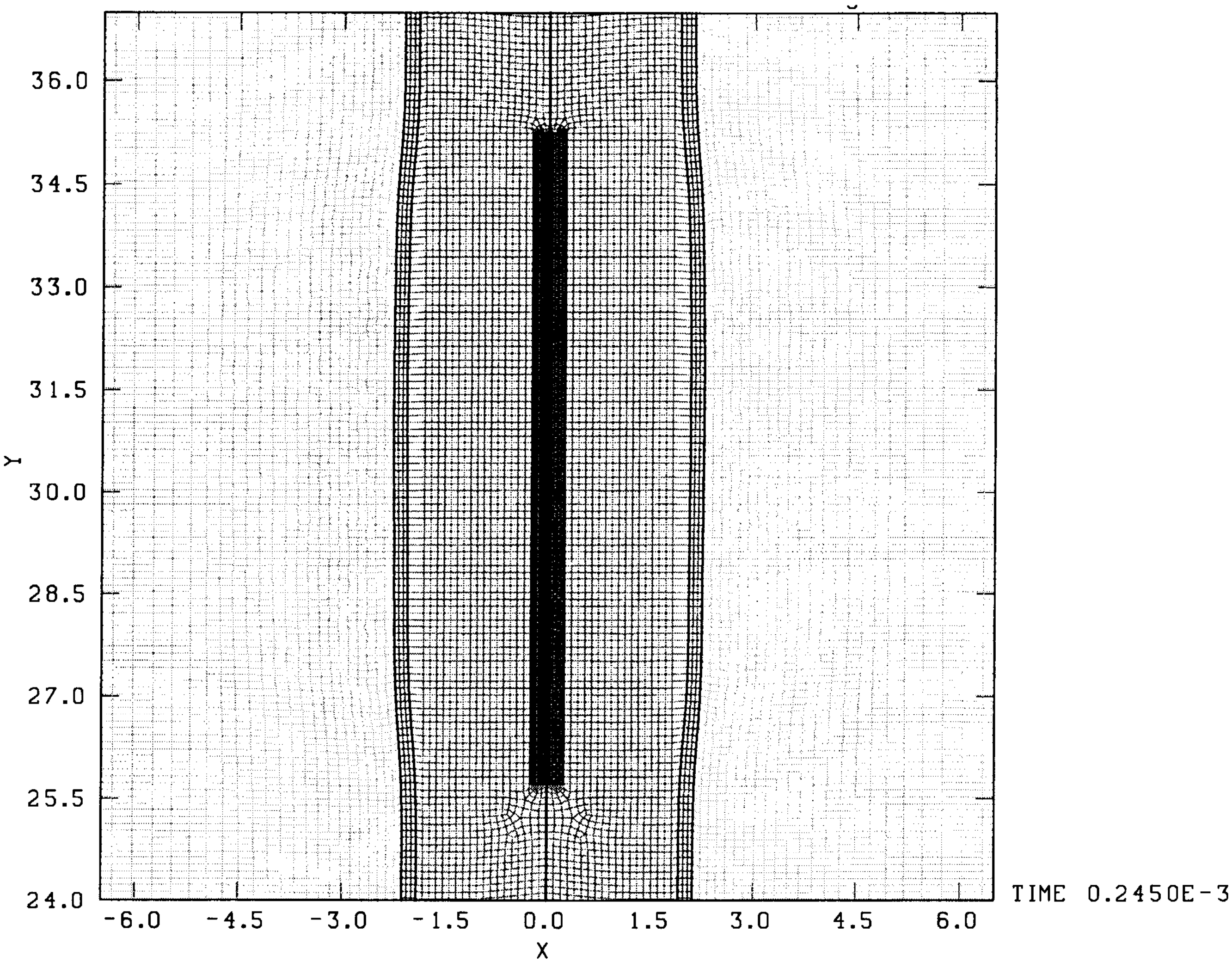

Figure 20. Final deformed shape predicted for the aluminum tube.

5.0 Conclusions

This work has demonstrated that a significant capability exists at Sandia National Laboratories for performing coupled explosive/structure interaction calculations. Smoothed Particle Hydrodynamics (SPH) coupled with three-dimensional finite elements provides one capability that was demonstrated by calculating the explosive loading on both a solid and a block explosive barrier wall.

The ALE code ALEGRA has been demonstrated by simulating a decoupled explosive in a tunnel. This code was used to design a scaled centrifuge experiment and a detailed two-dimensional ALEGRA analysis was used to better understand the experiment and to validate numerical methods.

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