Coupled Euler-Lagrange Simulation of the JOLT HE Event

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***Abstract**: We simulated the Defense Threat Reduction Agency (DTRA)-sponsored Jointed Limestone Test (JOLT) using the Abaqus fully coupled Euler-Lagrange computation scheme. JOLT was a small-scale experiment consisting of over 37,000 individual cubes of limestone surrounding simulated tunnels. This test bed was loaded with ground shock generated by a spherical Comp B charge, thereby providing data for the study of computer codes used to compute the response of buried tunnels to explosive loading. We modeled the cubes as continuum blocks with contact, making for a dis-continuum simulation using a hybrid continuum code including Eulerian modeling of the explosive region and Lagrangian modeling of the remainder of the test bed. This paper has been approved for unlimited release under **LA-UR-14-20056**.*

***Keywords**: Coupled Analysis, Explosive Effects, Geodynamics.*

1. Introduction

The Defense Threat Reduction Agency (DTRA) has funded studies of tunnel vulnerability to blast effects for decades. The studies have included experiments of various complexity and scale as well as numerical analysis. Several projects have combined computational studies with these experiments to validate predictive algorithms. Numerical approaches have evolved based not only on prior knowledge but also due to advances in computing hardware and software capabilities. The focus of this paper is on a recent three-dimensional (3-D) simulation effort, but we will also provide some background material by describing an older two-dimensional (2-D) computational effort that laid some of the groundwork for this later work.

2. MIGHTY NORTH

The MIGHT NORTH event was a lab-scale high explosive test performed in the mid-90s to investigate various approaches to numerical simulation of the response of tunnels to explosive-induced ground shock (Gran, *et al*, 1998). The test bed (Figure 1) consisted of 1.2-m long, 5-cm square cross-section bars of limestone stacked in an imbricate pattern to simulate a layered, jointed geologic setting. The “block of bricks” was 2 m square in section and 2 m long. The center of the block included a 0.4-m diameter aluminum “tunnel liner.”

The block was embedded within a larger block of concrete to mitigate spurious boundary effects within the simulation time of interest. A cylindrical trough was formed at the top of the concrete block for the placement of an explosive charge which was designed to produce a cylindrical shock front. This was intended to create a 2-D plane strain condition which would be the basis for numerical simulations of the test. The block of bricks included an array of accelerometers around the perimeter in the length-wise center to provide a kinematic boundary for driving the simulation.

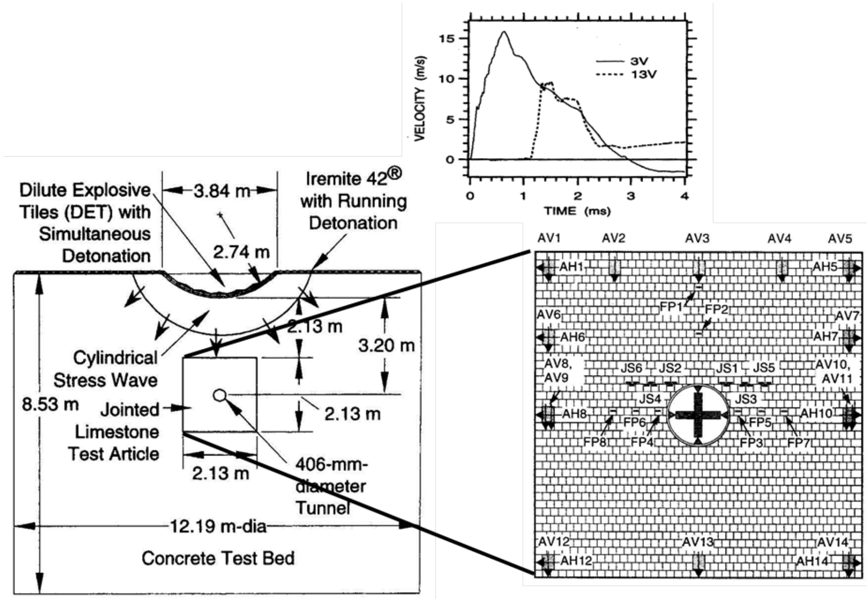

Figure 1. MIGHTY NORTH test bed.

A team of investigators was assigned to simulate the test bed response using their chosen computer method/code. Los Alamos National Laboratory (LANL) was not a participant in that program and the prior results will not be presented here. But reflecting our own interests in tunnel response phenomenology, in 2000 we determined to independently simulate MIGHTY NORTH using the Abaqus code.

We implemented a 2-D model (Figure 2) wherein each individual bar was explicitly modeled, including explicit contact to model bar-on-bar interaction. The limestone was modeled using the Abaqus brittle cracking model which assumes a linear elastic response prior to cracking. Brittle cracks are initiated as Mode I fractures (*i.e.*, tensile softening). After crack initiation both Mode I and Mode II (shear softening) occur. Total failure is defined after sufficient cracking strain is achieved. Properties for this model (*i.e.*, elastic modulus: E=30 GPa, Poisson's ratio: ν=0.3, bulk density, ρ=2710 kg/m^3, tensile strength, q_t=8 MPa, and cracking strain at failure, ε^f_{cr}=0.001) were based on data for Salem limestone (Senseny and Simons, 1994). There are some limitations of this model, such as the lack of an elastic-plastic pressure/excess compression equation-of-state (EOS) to model the crush behavior that is typical of geo-materials.

The aluminum liner was relatively thick and so was modeled with continuum elements populated with published elastic-plastic properties for the 6061-T0 aluminum used in the test. As the simulation was driven with actual recorded boundary motions, which turned out to be not perfectly symmetrical, we chose to model the entire cross-section rather than assume vertical symmetry.

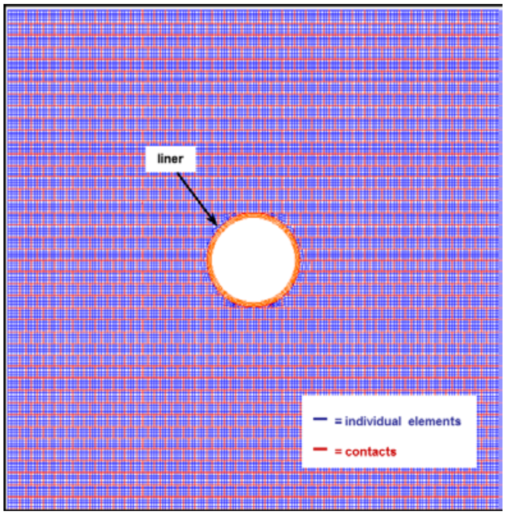

Figure 2. Abaqus model of the MIGHTY NORTH test bed.

The test bed was de-constructed after the experiment and the bar failures were recorded. Also, the liner was removed and its deformation was measured. These would form the basis for comparison of simulation results to the test.

Figure 3 shows a mapping of bars that cracked during the test. The figure also includes a contour plot distinguishing bars that experienced brittle failure (red) from those that did not (blue) in the numerical simulation. This qualitative measure of response indicates that the Abaqus simulation was successful in modeling the rock damage.

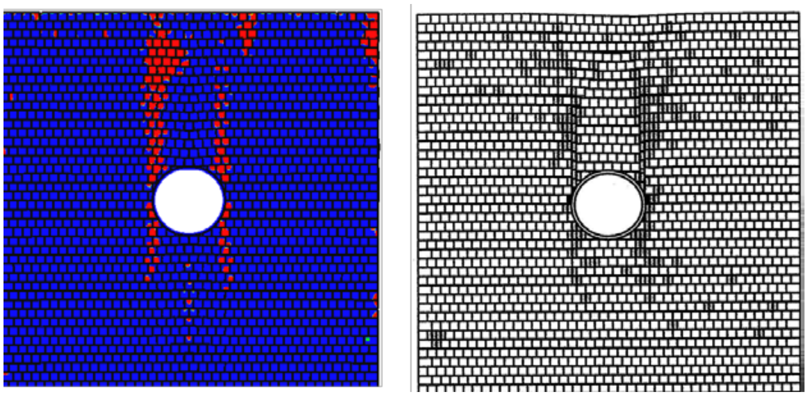

Figure 3. Material failure for the MIGHTY NORTH test; left: computed, right: measured.

Figure 4 is a comparison of measured and computed liner deformation modes. Table 1 is a comparison of absolute liner deformation in terms of shortening (crown-to-invert) or lengthening (springline-to-springline). Again the simulation matches the data and these results provided confidence in moving forward to more complex simulations.

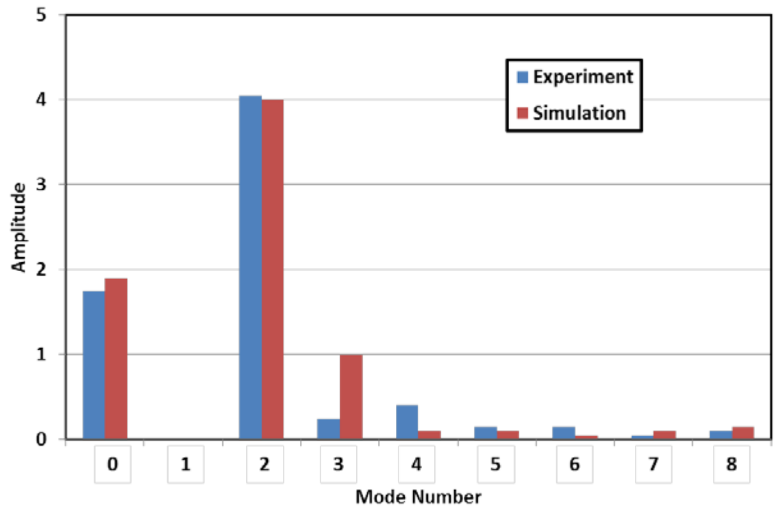

Figure 4. Measured and computed MIGHTY NORTH tunnel liner response Modes.

Table 1. Measured and computed MIGHTY NORTH tunnel liner deformation.

Liner Deformation	Measured (mm)	Computed (mm)
Crown to Invert	11.4	12.9
Springline to Springline	3.5	3.5

3. JOLT

The decade following the fielding of MIGHTY NORTH was accompanied by drastic improvements in computer hardware and software. In their continuing effort to improve understanding of tunnel response DTRA performed the Hard and Deeply Buried Target (HDBT) Advanced Concept Technology Demonstration (ACTD). The combined experimental/numerical analysis program was intended to identify an improved methodology for estimating explosive-caused damage on buried tunnels. In particular, the goal was to extend the gains from MIGHTY NORTH to higher fidelity 3-D methods. An extensive verification and validation effort using various codes and computation approaches was followed by a test series.

The experimental series again included laboratory-scale tests referred to as the JOinted Limestone Tests (JOLT) (Gran, 2007). Constructed and carried out at SRI International, these tests included spherical explosive sources to create shock through a jointed and layered limestone test bed which included two tunnels. Computation methods generally included performing an Eulerian calculation of the source and nearby rock to develop loading conditions for driving the rock response. A "one-way" approach was used to couple that loading to the main test bed which was modeled, depending on the modeling group, as either Arbitrary Lagrangian-Eulerian (ALE), Lagrangian, or discrete elements. The joints/layers were variously modeled as contact surfaces, contact elements, and continuum elements with contact. The simulations had limited success in replicating both the active data and the tunnel damage in the tests.

Subsequent to the original effort, SIMULIA released the fully coupled Euler-Lagrange capability in Abaqus (CEL) which was developed in partnership with LANL. We recently tested this capability for blast and shock applications by re-visiting the JOLT simulation. We took advantage of being able to perform the simultaneous solution of an Eulerian source region with a Lagrangian test bed for more accurate modeling than is allowed through one-way coupled approaches. A robust contact algorithm allows for modeling of the individual limestone blocks as separate continuum entities without reverting to a discrete element approach. The following discussion presents results of the JOLT simulation using this approach, including comparing the simulation to the test response.

3.1 Test description

The JOLT test bed, illustrated in Figure **5**, included 0.6096-m (24-in) square, 0.0127-m (½-in) thick Salem limestone plates, cracked at 0.0127-m intervals in orthogonal directions to form cubes. Sixty-five cracked plates were stacked, and alternating the crack patterns provides for an imbricate pattern in the vertical joints. Large blocks of limestone were placed above and below the plates, and grout and concrete were poured around the test bed to extend the boundaries. A 0.680-kg sphere of Composition B (CompB) explosive was detonated above the layered test bed. Two 0.1016-m (4-in) diameter cylindrical holes were drilled through the plates to represent tunnels. Data acquisition included accelerometers and stress gauges to provide active data, and post-test deconstruction to document damage and deformation of the test bed.

3.2 Simulation description

The JOLT test bed was modeled using Abaqus/CEL. This included an Euler domain for the high-deformation explosive source region and a Lagrange domain for the complex response within the rock. CEL allows for simultaneous solution and full coupling between the two domains to properly model the multi-physics interaction. The Euler domain included both the explosive volume region and a void region that overlaps the surrounding rock to compensate for rock cratering and gas expansion. Contact occurs between the Eulerian material surface (in this case the detonation products) and the Lagrange solid. The explosive was modeled as a JWL EOS with published constants for CompB (Lee, *et al*, 1968). The explosive EOS was center-detonated with a programmed burn. Figure 6 illustrates the ¼-symmetry CEL computational model.

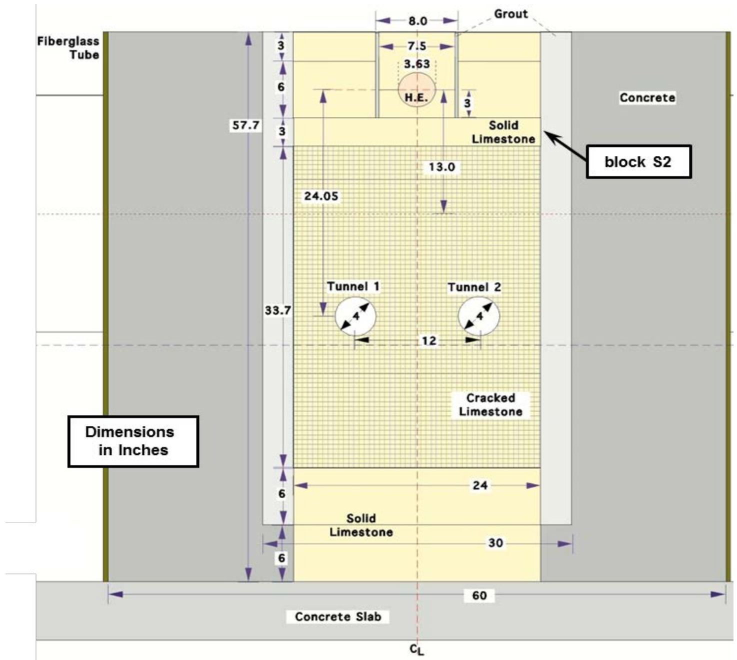

Figure 5. JOLT test bed.

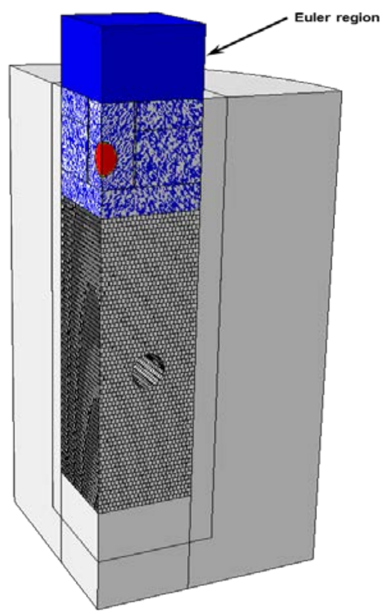

Figure 6. Abaqus/CEL model.

The Lagrange domain included the limestone blocks, the cracked limestone plates, the grout and the concrete. In ¼-symmetry this makes 576 cubes per layer, or 37,440 cubes total within 65 layers, minus those cubes removed to accommodate the tunnel. Each limestone cube included a 3 x 3 x 3 mesh of continuum elements. JOLT used the same brittle cracking model for the limestone as was used in the MIGHTY NORTH simulation described earlier in this paper.

The block contacts were modeled using simple Coulomb friction with non-compliant ("hard") normal contact. The plate surfaces were ground smooth prior to cracking and so might have had relatively low friction, although this parameter was not measured in the laboratory. On the other hand, the vertical surfaces were formed by cracking and so were quite rough and would have high friction (also not measured). As no values for surface friction were determined we chose as a compromise a friction coefficient of 1 in for the entire general contact domain. A more accurate differentiation between the two types of surfaces might result in an improved model.

The simulation was taken to a15-ms duration. This is sufficient to capture the dynamic response of the test bed, although complete kinematic response and return to equilibrium requires considerably more time.

3.3 Results

A comparison between the post-test photograph of the top of the rubblized test bed and the final configuration of the top of the model is included in Figure 7. **Mirror** imaging was performed on the model symmetry planes to create a 360° image.

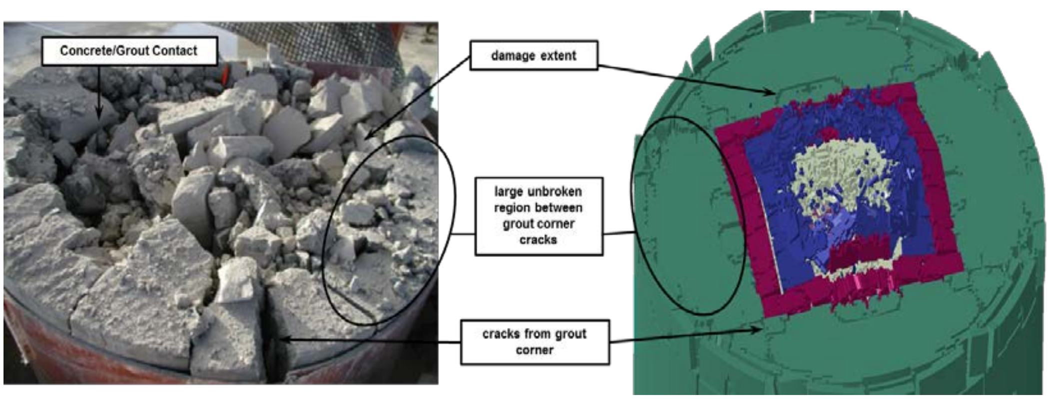

Figure 7. Final configuration of the top of the test bed; top: test, bottom: simulation.

The following similarities between the two images are observed:

- The rubble region extends to the grout/concrete interface.
- There are regions of closely spaced radial cracks intermittent with regions of longer undamaged pieces of concrete. In the simulation, we see that these radial cracks emanate from the square corners of the grout/concrete interface.
- The side of the experiment furthest from the camera appears to have experienced a more complete blow-out indicating that there was not perfect symmetry in the experiment.

A comparison between a post-test photograph of the top of block S2 and the final computed configuration of the top of block S2 in the model is included in Figure 8.

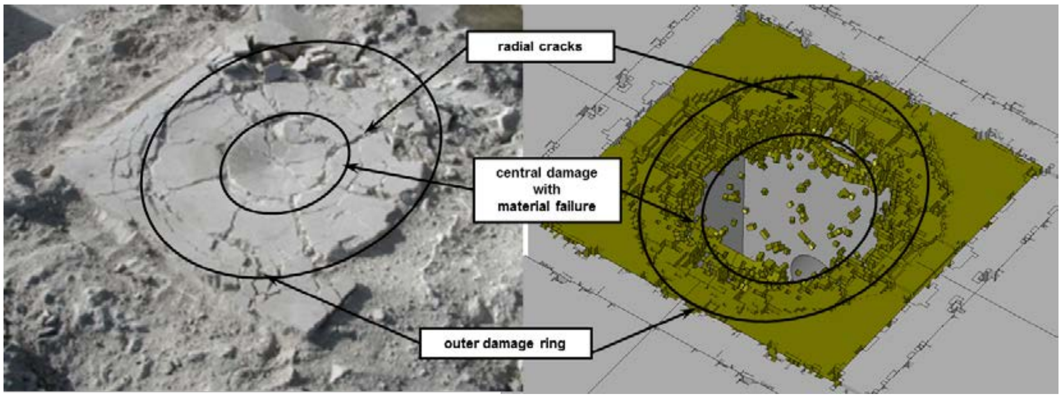

Figure 8. Final configuration of top of block S2; top: test, bottom: simulation.

The following observations can be made:

- The photograph displays a central region of greatest deflection and crushed material. The elements in the model in a similar region were deleted due to material failure.
- Both images include a larger circular region of cracking near to the edges.
- The photograph indicated radial cracks connecting the dimpled region and the outer circular cracked region. This character is not as apparent in the simulation due to element deletion but radial cracking is evident in that image.

A comparison between a post-test photograph of the top of layer 51 and the final computed configuration of the top of layer 51 in the model is included in Figure 9.

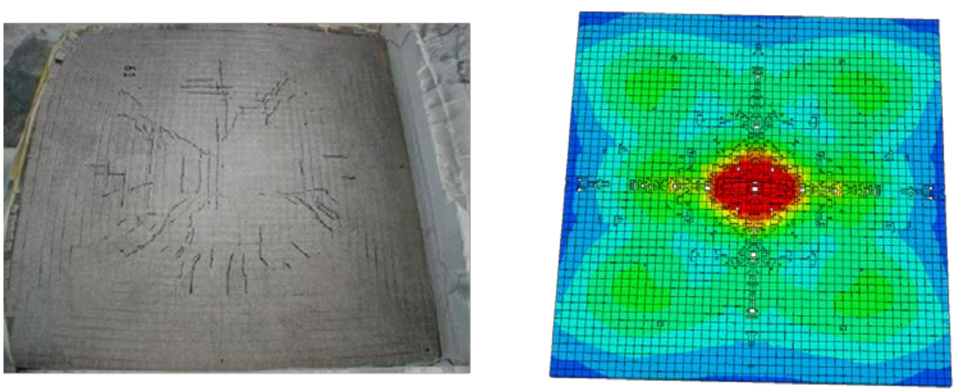

Figure 9. Plate 51 damage; top: test, bottom: simulation.

The following observations can be made:

- Both images include a circular “dimpled” region in the center of the plate.
- Both images include a larger circular region of cracking. There is a difference, though, in that the test caused radial cracking while the computed cracks have no distinct pattern. Note that the “cross” pattern in the simulation exists on the symmetry boundaries of the simulation suggesting a concentration of shock reflections in perfect symmetry. While we noted earlier (in Figure 7) that full symmetry likely did not occur in the test, cracking along a symmetry line (vertical in the photograph) is apparent.

The above comparisons provide qualitative assessments of the simulation. But there also can be made quantitative comparisons between the test and the computation. For example, Figure 10 is a plot of peak vertical stress vs. depth for gauges placed on the vertical axis of the test bed below the explosive center. The figure includes both recorded and computed values. The simulation is close to the data near to the source but there is increasing divergence with depth. This less steep attenuation in the simulation is likely due to the lack of shock absorbing compression in the rock EOS.

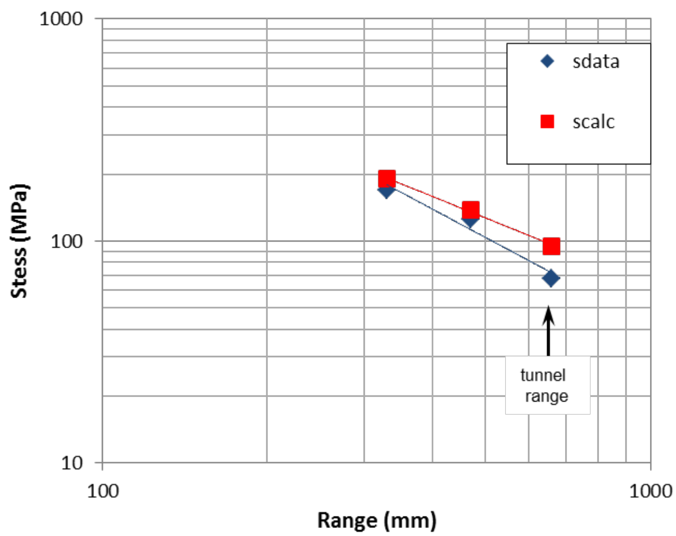

Figure 10. Recorded and calculated peak on-axis vertical stress with depth.

Figure 11 is a plot of peak vertical velocity vs. depth down-axis from the explosive center, including both derived data (integrated accelerometer histories) and computed values. The simulation is about two-thirds of the amplitude of the data near to the source. The curves converge with depth, with the simulation velocity being about 10% lower than the data at the tunnel depth.

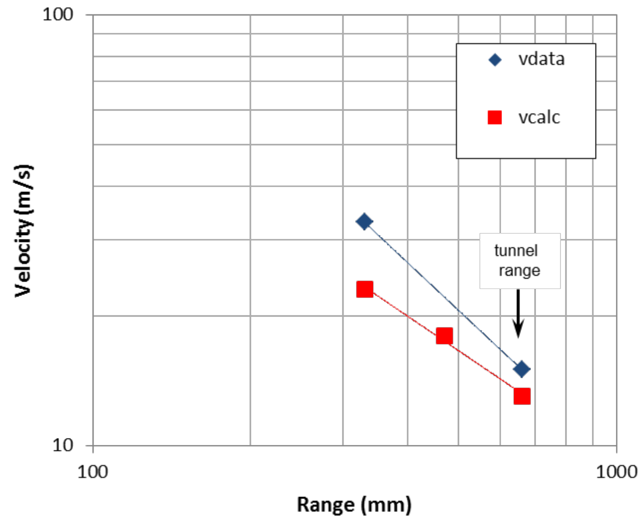

Figure 11. Recorded and calculated peak on-axis vertical velocity with depth.

Figure 12 and Figure 13 show tunnel damage. A view looking down the axis of the test tunnel and of the simulated tunnel collapse is shown in Figure 12. Note that a balloon was inserted into the test tunnel after the event to preserve the final configuration. Also, note that the final configuration in the simulation includes contours of scalar velocity (speed). The photographs show the rubble in the tunnel (left) and the arching caused by loss of support through creation of the rubble (center).

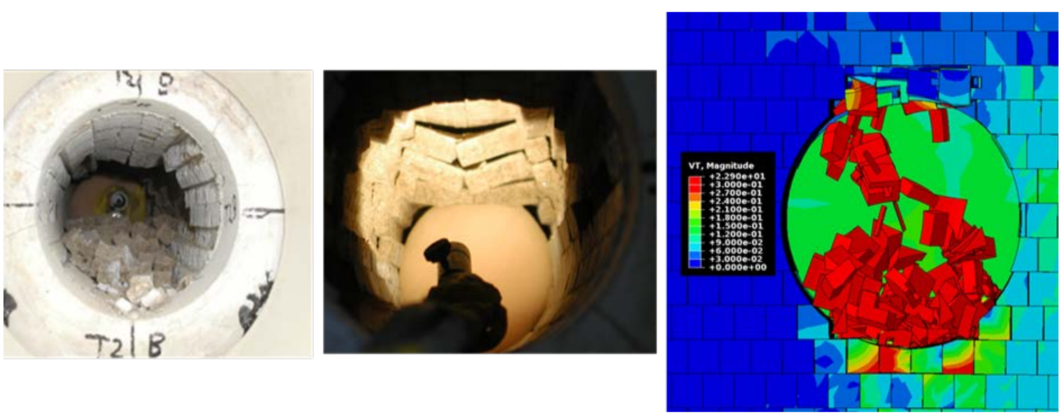

Figure 12. Damage down the tunnel axis; left and center: test, right: simulation.

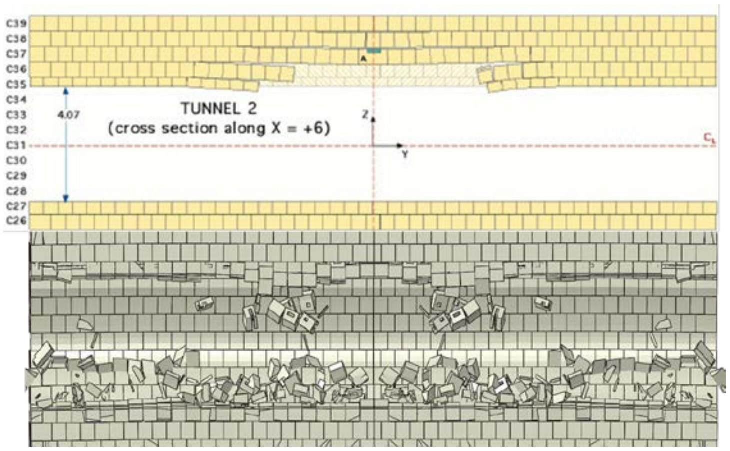

Figure 13. Damage down axis; top: test, bottom: simulation.

In summary:

- In the test, the two rows above the tunnel crown, axially near to the center of the test bed, collapsed. Layers above this remained in place due to arching.
- The first two layers above the crown have collapsed by the end of the simulation. It is reasonable to assume that cubes with 0, or near 0, speed (blue contours) at this point in the calculation would not undergo addition displacement with continued simulation. It follows that no additional layers will collapse into the tunnel. However, the collapsed cubes in the simulation extend further down the axis than in the test. Possibly the proper modeling of the different friction coefficients between the vertical and horizontal surfaces could improve this character.
- Generally, these comparisons suggest an accurate simulation.

Finally, Figure 14 provides snapshots of scalar velocity contours at two intermediate times in the simulation. The left figure is at 100 μs simulation time. This figure demonstrates that the spherical shock front generated by a spherical charge remains spherical despite the frequent occurrence of three joint sets. The right figure, taken at 200 μs simulation time, illustrates how the shock front is perturbed by the tunnels.

4. Summary

We demonstrated the use of the multi-physics Abaqus fully coupled Euler-Lagrange code to model the DTRA JOLT experiment. Abaqus/CEL was able to compute the high-deformation explosive loading, the complex rock response with damage, and the large general contact domain. Comparison of results to test data reveals that the simulation performed credibly.

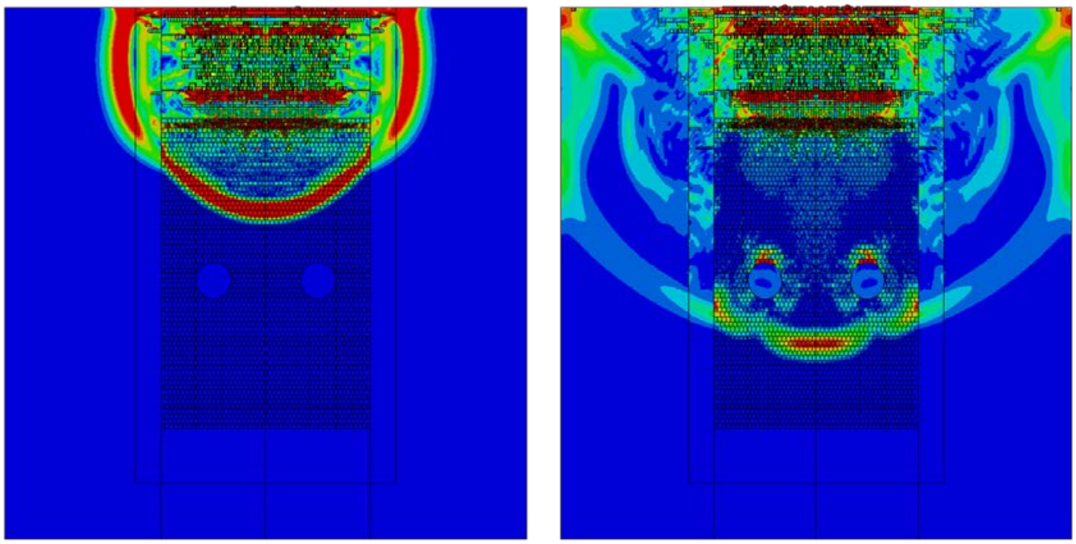

Figure 14: Computed scalar velocity contours; left: 100 □s, right: 200 □s.

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5. References

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