SCIENTIFIC NOTEBOOK 789E

REVIEW OF BECHTEL SAIC COMPANY, LLC REPORT TITLED "PEAK GROUND VELOCITIES FOR SEISMIC EVENTS AT YUCCA MOUNTAIN, NEVADA, ANL-MGR-GS-000004, REV. 00"

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OBJECTIVES

This scientific notebook documents numerical models conducted in support of staff review of the DOE peak ground velocity (PGV) report (Bechtel SAIC Company, LLC, 2005). The numerical modeling was accomplished with the commercial-off-the-shelf code ABAQUS (Hibbit, Karlsson, & Sorensen, Inc., 2005).

SPECIFIC TASKS

This notebook documents Abaqus finite element models that were analyzed in support of the staff review of the PGV report. The specific models were

1. ABAQUS/Standard analysis of a sliding interface.
2. ABAQUS/Explicit analysis of a sliding interface.
3. ABAQUS/Standard analysis of a thin deformable zone.

BACKGROUND

The basic problem involves the dynamic response of a planar discontinuity subjected to a normally incident plane harmonic shear wave. The geometry of the problem (Fig. 1) consists of a rock discontinuity of infinite extent that lies within an infinite, homogeneous, isotropic, and elastic rock mass. The shear strength (t_s) of the discontinuity surface is characterized by zero friction angle and nonzero cohesion, which implies a constant shear strength (independent of normal stress). As a result, the discontinuity will slip if the transient shear stress induced by the shear wave equals or exceeds the cohesion. If slip occurs, the energy of the incident wave is partitioned between reflected and transmitted waves, and absorption at the interface.

The problem has been previously analyzed using UDEC (Brady et al., 1990) and ABAQUS (Ghosh et al., 1994; Ofoegbu et al., 1995). The geometry of the model and the finite element mesh as used in the previous analyses is shown in Figure 2. It is 600 m in height and 80 m in width. Plane strain conditions were assumed in the analysis and the vertical boundaries were restrained vertically (y velocity = 0). The discontinuity was horizontal at y = 0. Infinite elements were placed at the horizontal boundaries, GH and CD, to create absorbing boundaries for simulating infinite material to wave propagation analysis. The harmonic shear wave was applied at a depth of 200 m below the interface. The shear stress history was monitored at two points, A and B, located at

195 m below and above the discontinuity, respectively.

The elastic medium was simulated using 8-node quadrilateral elements and the discontinuity with 6-node interface elements. At the time these analyses were performed, there was no direct way to apply shear stress on the surface of solid elements in ABAQUS. Therefore, 3-node beam elements were placed at y= -200 m, coincident with the base of a row of quadrilateral elements located at that elevation. Axial force was applied in the beam elements to transmit the desired magnitude of shear stress to the base of the quadrilateral elements. The stiffness of the beam elements was set to a small value relative to that of the solid elements. Material properties for the elastic medium were:

- Young's modulus, E = 25 GPa
- Poisson's ratio, ν = 0.25
- Density, ρ = 2.65 kg/m^3

Material properties for the beam were:

- Young's modulus, E = 0.025 MPa
- Poisson's ratio, ν = 0.25
- Density, ρ = 2.65 kg/m^3
- Friction angle, ϕ = 0°

The applied axial force (F) varied according to the following equation:

$$F = A\sin(2\pi t)$$

where A is 2.0 MN/m and t is time in seconds. This produced a sinusoidal shear wave of amplitude 2.0 MPa at the base of the neighboring row of quadrilateral elements, thereby transmitting a horizontal shear stress wave of amplitude 1.0 MPa vertically through the medium. The shear strength of an interface was defined by a modification to ABAQUS friction law that allowed for the inclusion of a cohesion term:

$$\tau = \mu\sigma_n + C_o$$

where μ is the friction coefficient ($\mu = \tan\phi$), σ_n is the normal stress on the interface, and C_o is the cohesion. Cohesion values of 5.0, 0.75, 0.5, and 0.25 MPa were used in the analyses.

Examples of the ABAQUS analysis results for cohesion values of 5 and 0.5 MPa are shown in Figs. 3 and 4.

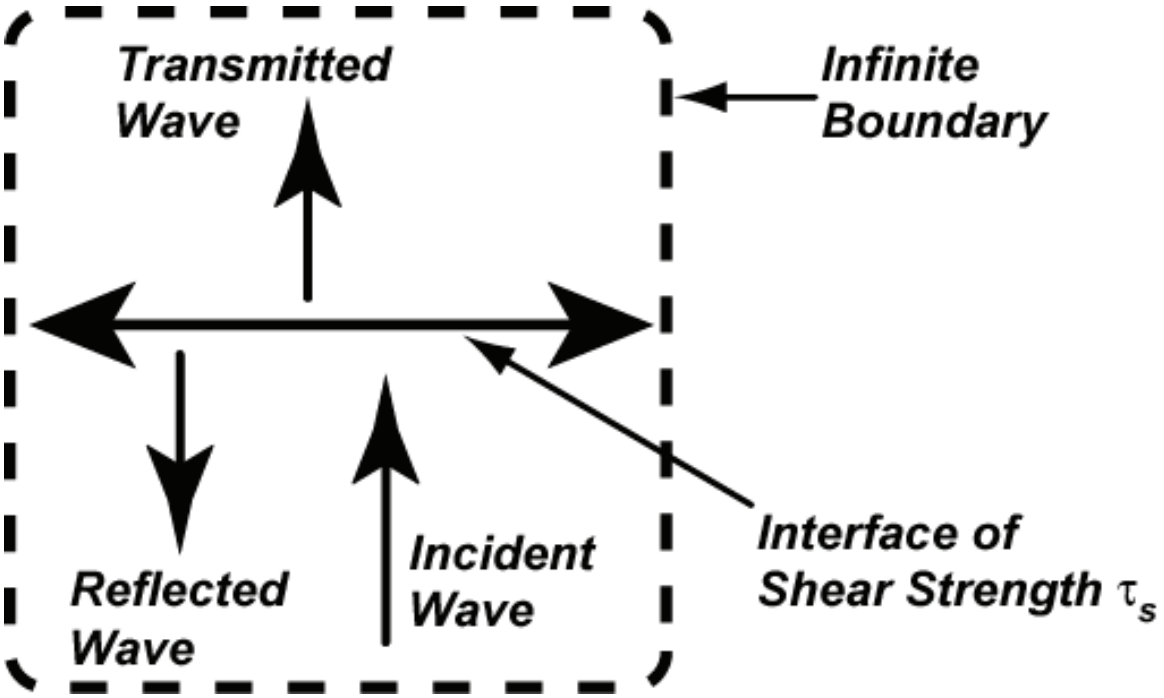

Figure 1. Problem definition -- wave propagation in an elastic medium with a single horizontal joint.

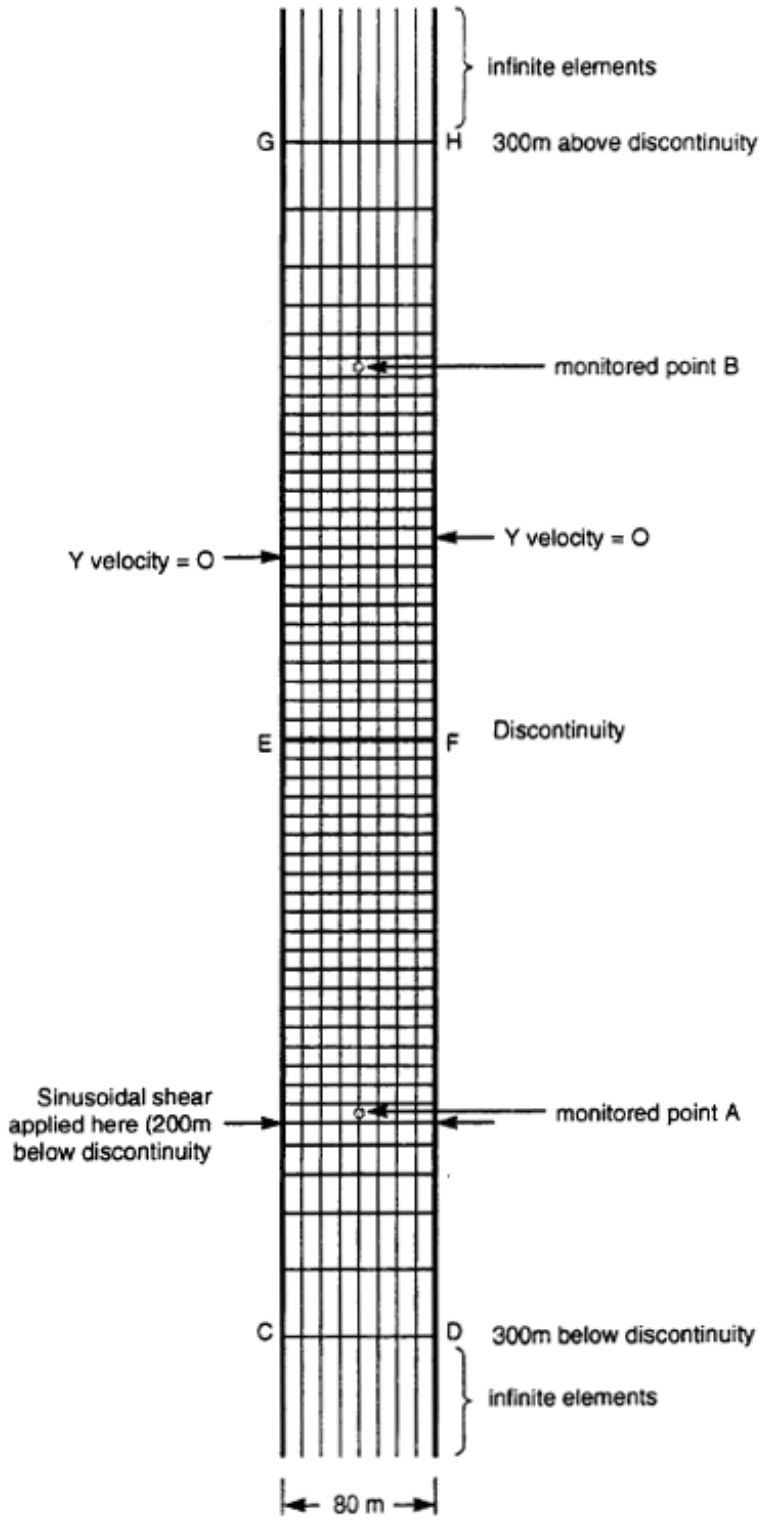

Figure 2. ABAQUS results for interface shear stress of 5 MPa (from Ofoegbu et al., 1995, figure 2-8, p. 2-9). Point A is 195 m below the discontinuity. Point B is 195 m above the discontinuity.

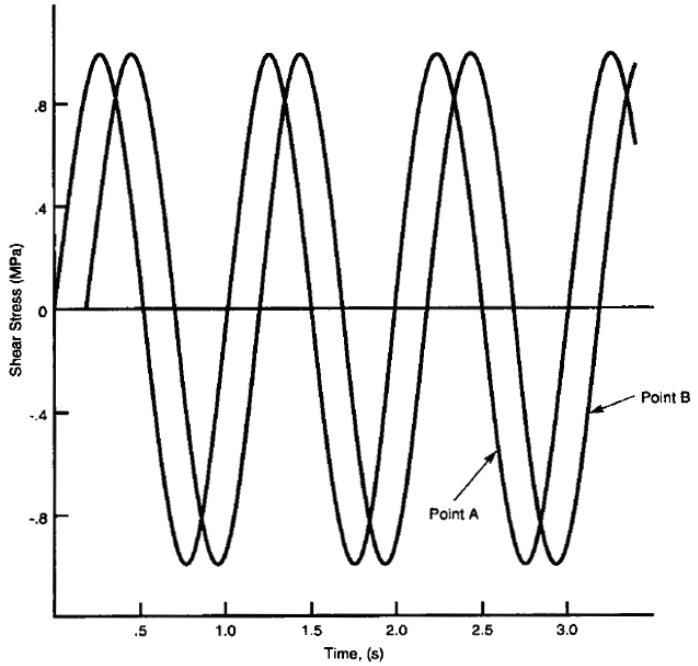

Figure 3. ABAQUS results for interface shear stress of 5 MPa (from Ofoegbu et al., 1995, figure 2-8, p. 2-9). Point A is 195 m below the discontinuity. Point B is 195 m above the discontinuity.

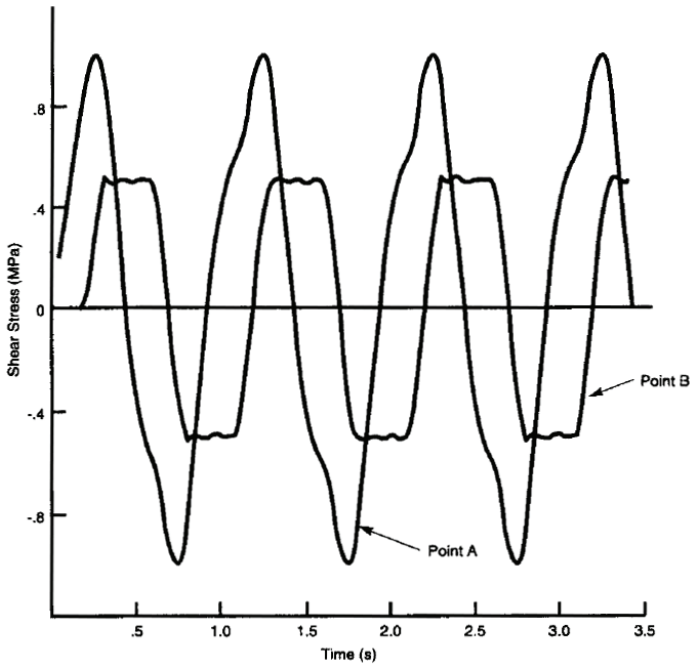

Figure 4. ABAQUS results for interface shear stress of 0.5 MPa (from Ofoegbu et al., 1995, figure 2-8, p. 2-9). Point A is 195 m below the discontinuity. Point B is 195 m above the discontinuity.

NEW INTERFACE ANALYSES

As part of the staff review of the PGV report (Bechtel SAIC Company, LLC., 2005), the basic problem was re-analyzed with the current version of ABAQUS (version 6.5-6). Although the new models are generally the same as those run previously, some differences do exist:

- The interface formulation in the current version of ABAQUS now includes the cohesion term (C_o) so that it was unnecessary to use the modified friction subroutine.
- The current version of ABAQUS now permits a shear stress load to be applied directly to a surface defined along the sides of solid elements so it was unnecessary to deploy beam elements.
- The elastic medium was constructed with 4-node bilinear elements with reduced integration and hourglass control (CPE4R) rather than the higher-order 8-node elements.
- The density was set to a more realistic value for rock of 2650 kg/m^3.

The elastic medium was assigned a Young's modulus of 25 GPa and a Poisson's ratio of 0.25. The friction angle for the interface was set to zero. The input shear stress wave had a magnitude of 1.0 MPa, consistent with the earlier analyses.

The analyses were conducted with ABAQUS/Standard and ABAQUS/Explicit for a 5 MPa cohesion. The ABAQUS input files are `Interface_5MPa_Standard.inp` and `Interface_5MPa_Explicit.inp`, and the shear stress loading condition was defined by the input file `Shear-Force.inp`. The ABAQUS results files are `Interface_5MPa_Standard.odb` and `Interface_5MPa_Explicit.odb`. As Figs. 5 and 6 demonstrate, neither the new ABAQUS/Standard nor the new ABAQUS/Explicit analysis provides the correct shear stress values at the monitoring locations (compare to Fig. 3).

The analyses were also conducted with 0.5 MPa cohesion. The input files are `Interface_0.5MPa_Standard.inp` and `Interface_0.5MPa_Explicit.inp`. The ABAQUS results files are `Interface_0.5MPa_Standard.odb` and `Interface_0.5MPa_Explicit.odb`. As Figs. 7 and 8 demonstrate, neither analysis provides the correct shear stress values at the monitoring locations (compare to Fig. 4).

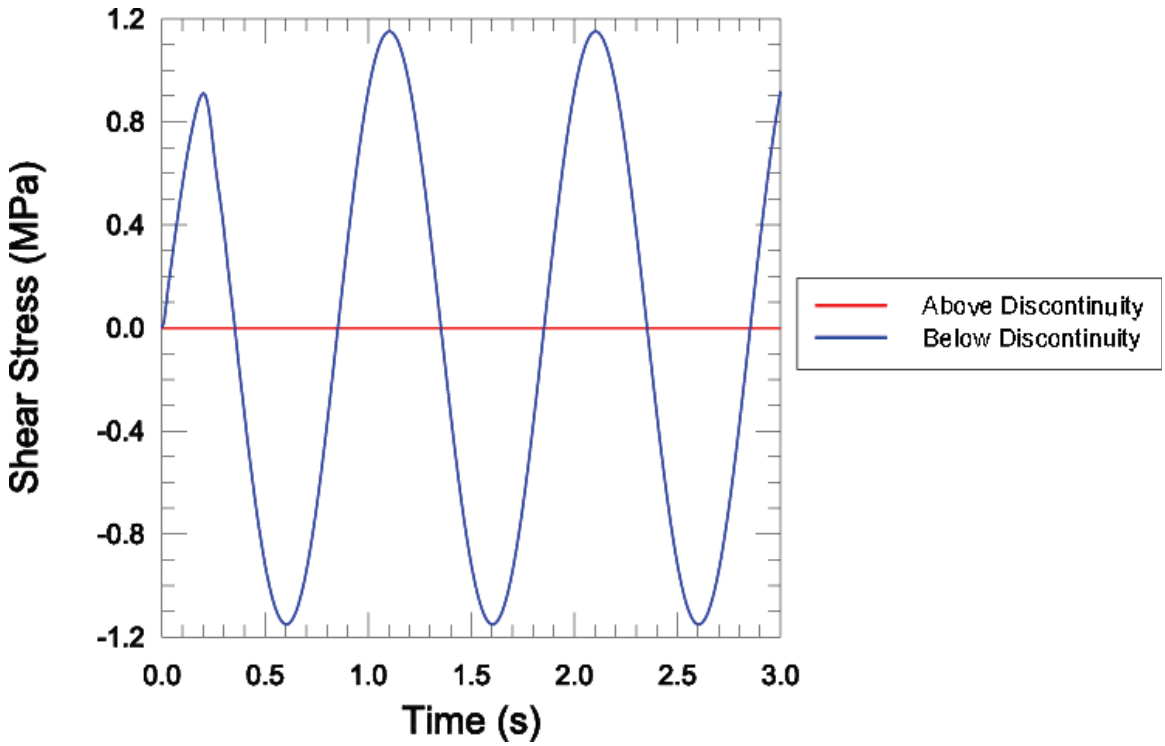

Figure 5. Analysis results from ABAQUS/Standard with a cohesion of 5 MPa.

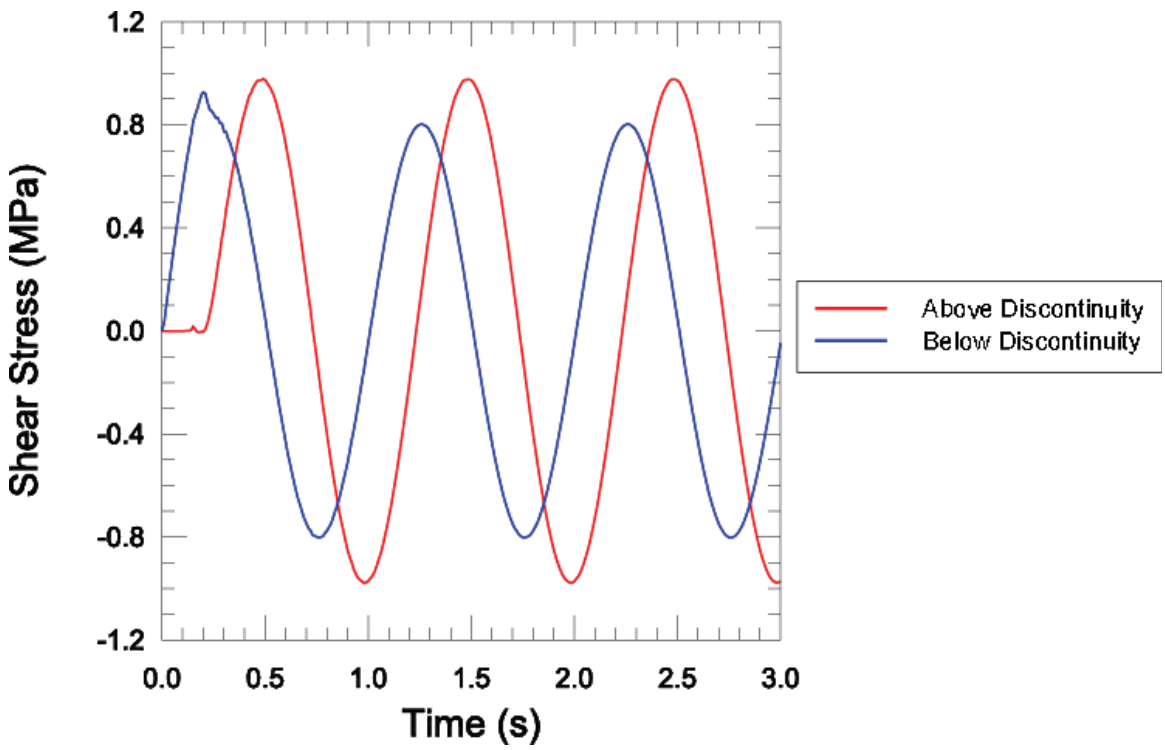

Figure 6. Analysis results from ABAQUS/Explicit with a cohesion of 5 MPa.

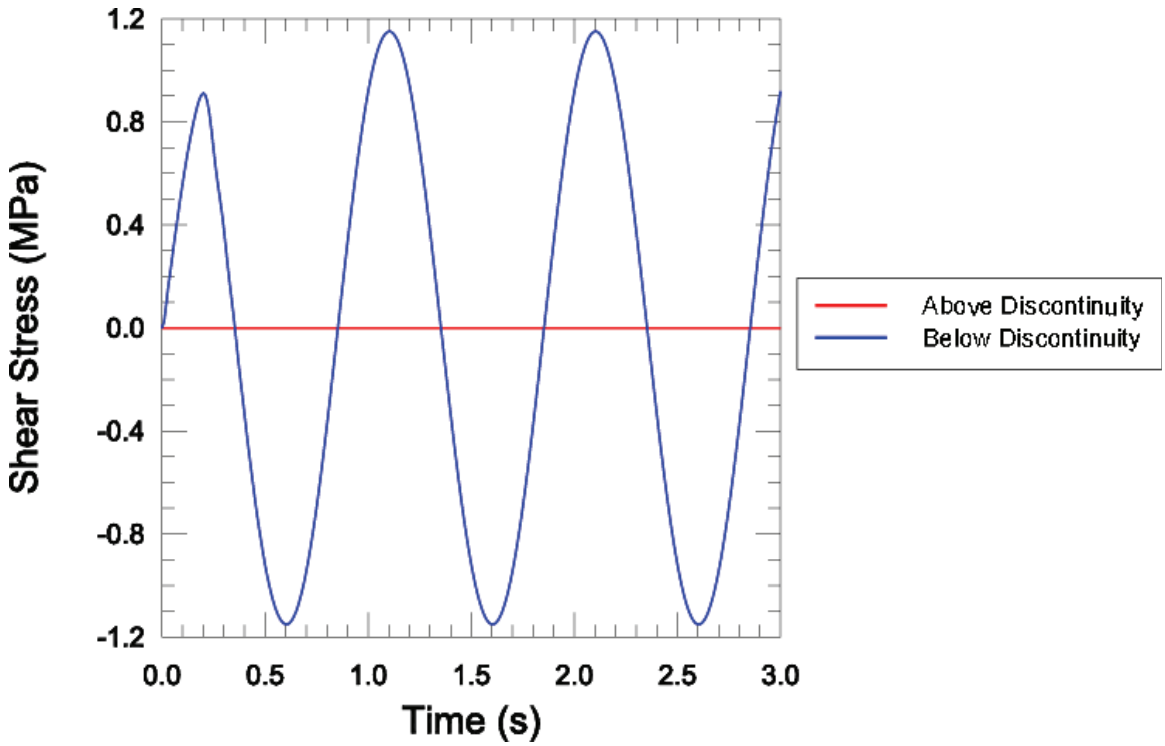

Figure 7. Analysis results from ABAQUS/Standard with a cohesion of 0.5 MPa.

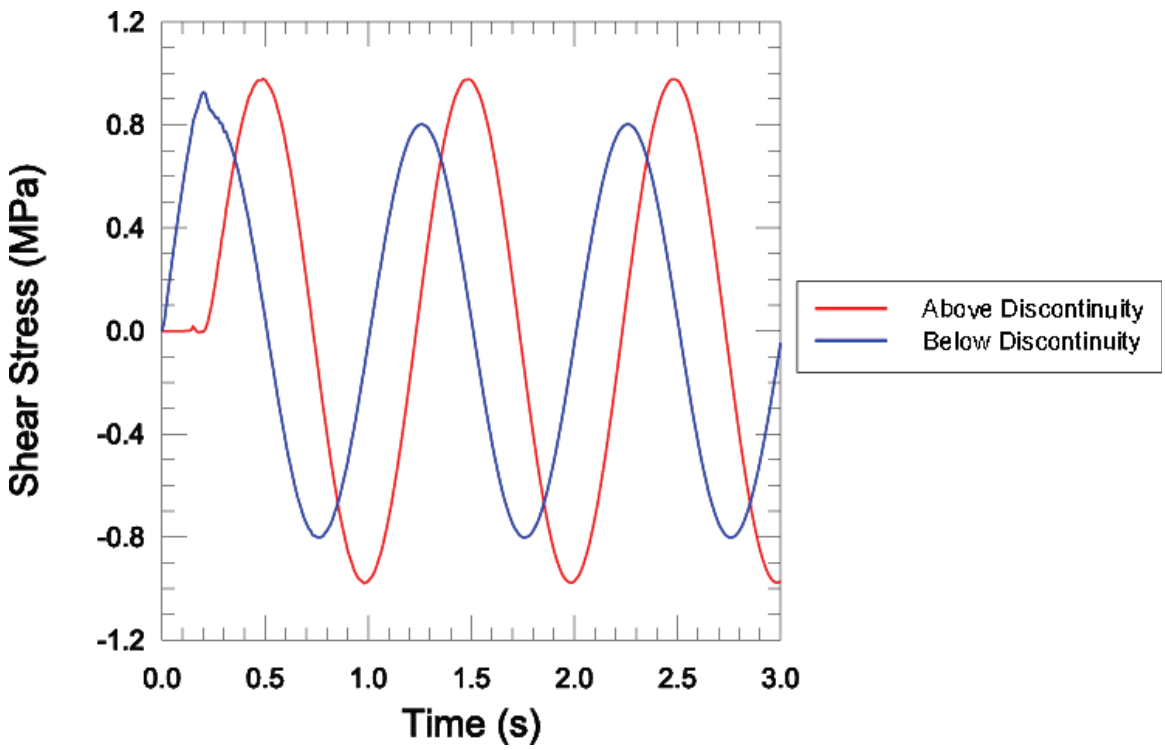

Figure 8. Analysis results from ABAQUS/Explicit with a cohesion of 0.5 MPa.

THIN DEFORMABLE-ZONE ANALYSES

In an effort to understand the incorrect results obtained with new version of ABAQUS, the problem was reformulated so that the sliding interface was replaced with a thin zone of deformable material. The deformable zone was assigned an elastic-plastic (i.e., Mohr-Coulomb) constitutive relationship with the friction and dilation angles set to a nearly zero value (0.01°). This configuration ensured that the strength of the thin zone would be controlled by the assigned cohesion value. For this analysis, the thin zone was 5 m thick, which is < 1% of the 600 m model height. Elastic material parameters were kept the same as the previous analyses. The input shear stress wave had a magnitude of 1.0 MPa, consistent with the earlier analyses, and was defined by the input file `Shear-Force.inp`.

The analysis was conducted with ABAQUS/Standard for a 5 MPa cohesion. The ABAQUS input file is `ThinZone_5MPa_Standard.inp` and the results files is `ThinZone_5MPa_Standard.odb`. As Fig. 9 demonstrates, the ABAQUS/Standard analysis provides the correct shear stress values at the monitoring locations (compare to Fig. 3).

The analyses were also conducted with 0.75, 0.5, and 0.25 MPa cohesion values. Input and output files are:

`ThinZone_0.75MPa_Standard.inp`	`ThinZone_0.75MPa_Standard.odb`
`ThinZone_0.5MPa_Standard.inp`	`ThinZone_0.5MPa_Standard.odb`
`ThinZone_0.25MPa_Standard.inp`	`ThinZone_0.25MPa_Standard.odb`

Results for cohesion values of 0.75, 0.50, and 0.25 MPa, respectively, are shown in Figs. 10, 11, and 12.

To further support the staff review of the PGV report (Bechtel SAIC Company, LLC., 2005), the horizontal components of the velocity and acceleration were extracted at the monitoring locations along with the shear stress. These results are tabulated in `ThinZone_Results.xls` (worksheet `1_MPa_Shear_Stress`) for each of the four input cohesion values.

To further support the staff review of the PGV report (Bechtel SAIC Company, LLC., 2005), the analysis with a cohesion value of 0.75 MPa were re-analyzed with two different input shear stress wave of amplitude 2.0 and 3.0 MPa. The input files are `ThinZone_0.75MPa_Standard-2.inp`, `ThinZone_0.75MPa_Standard-3.inp`., `Shear-Force-2.inp`, and `Shear-Force-3.inp`. These results are tabulated in `ThinZone_Results.xls` (worksheets `2_MPa_Shear_Stress` and `3_MPa_Shear_Stress`).

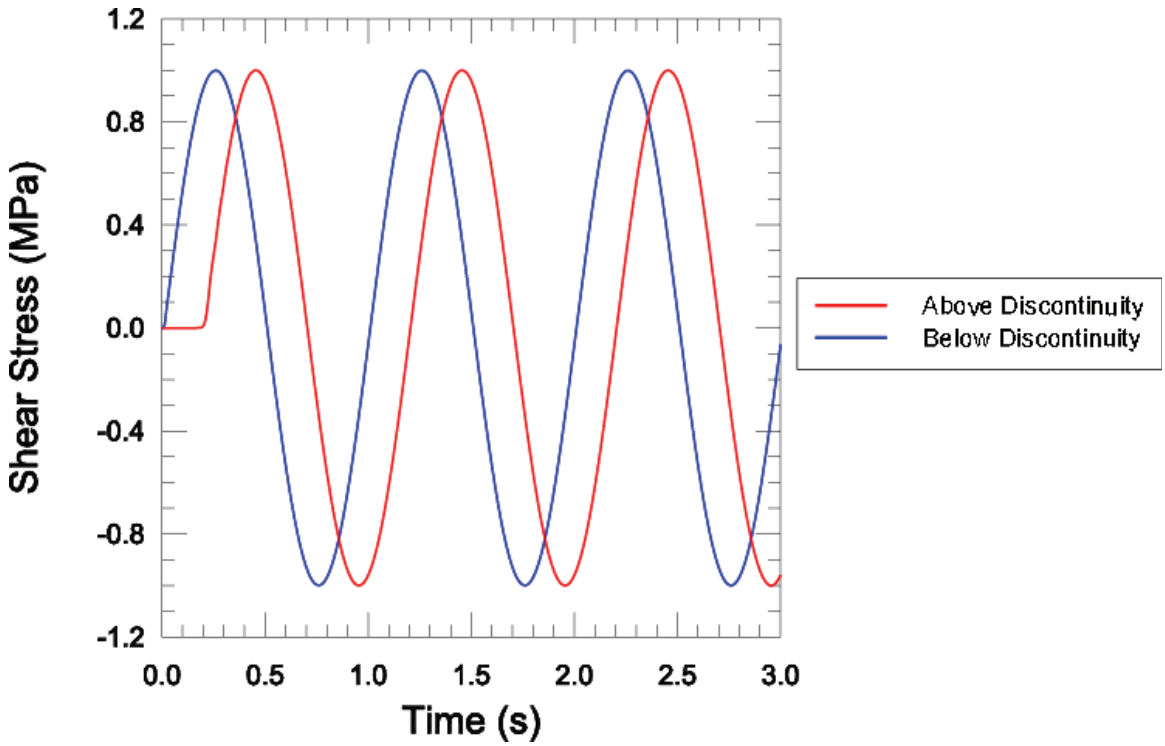

Figure 9. Analysis results from ABAQUS/Standard with a cohesion of 5 MPa for the thin deformable zone.

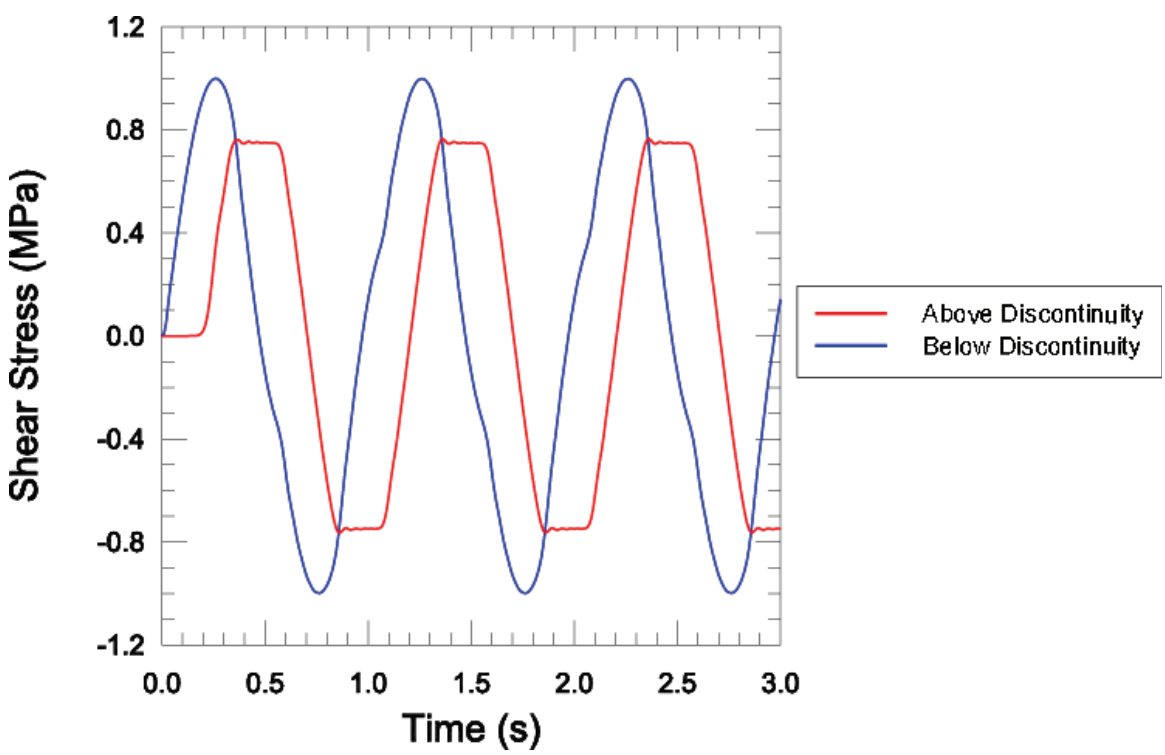

Figure 10. Analysis results from ABAQUS/Standard with a cohesion of 0.75 MPa for the thin deformable zone.

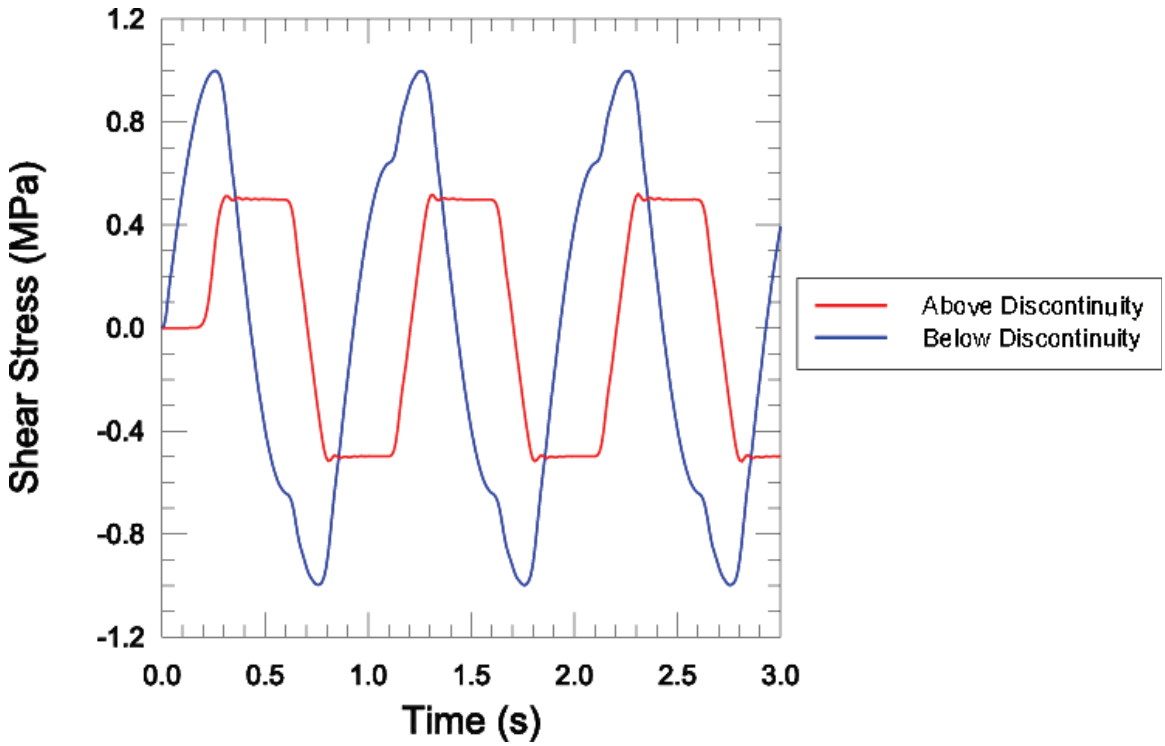

Figure 11. Analysis results from ABAQUS/Standard with a cohesion of 0.50 MPa for the thin deformable zone.

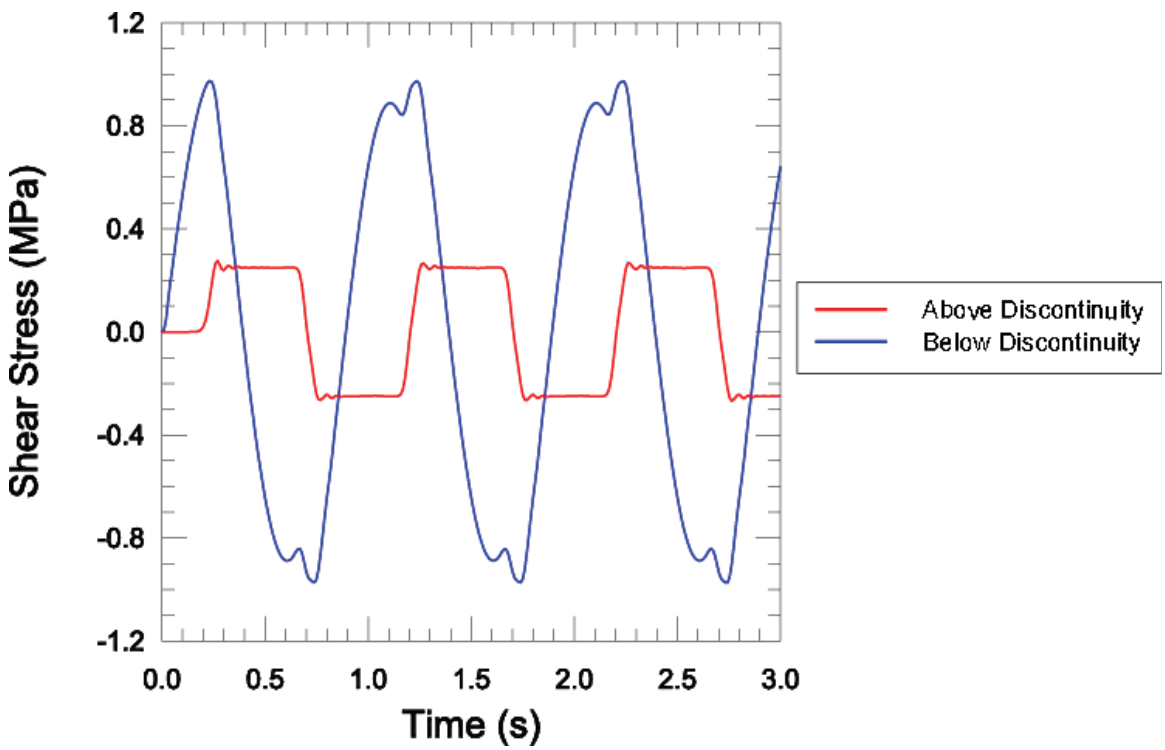

Figure 12. Analysis results from ABAQUS/Standard with a cohesion of 0.25 MPa for the thin deformable zone.

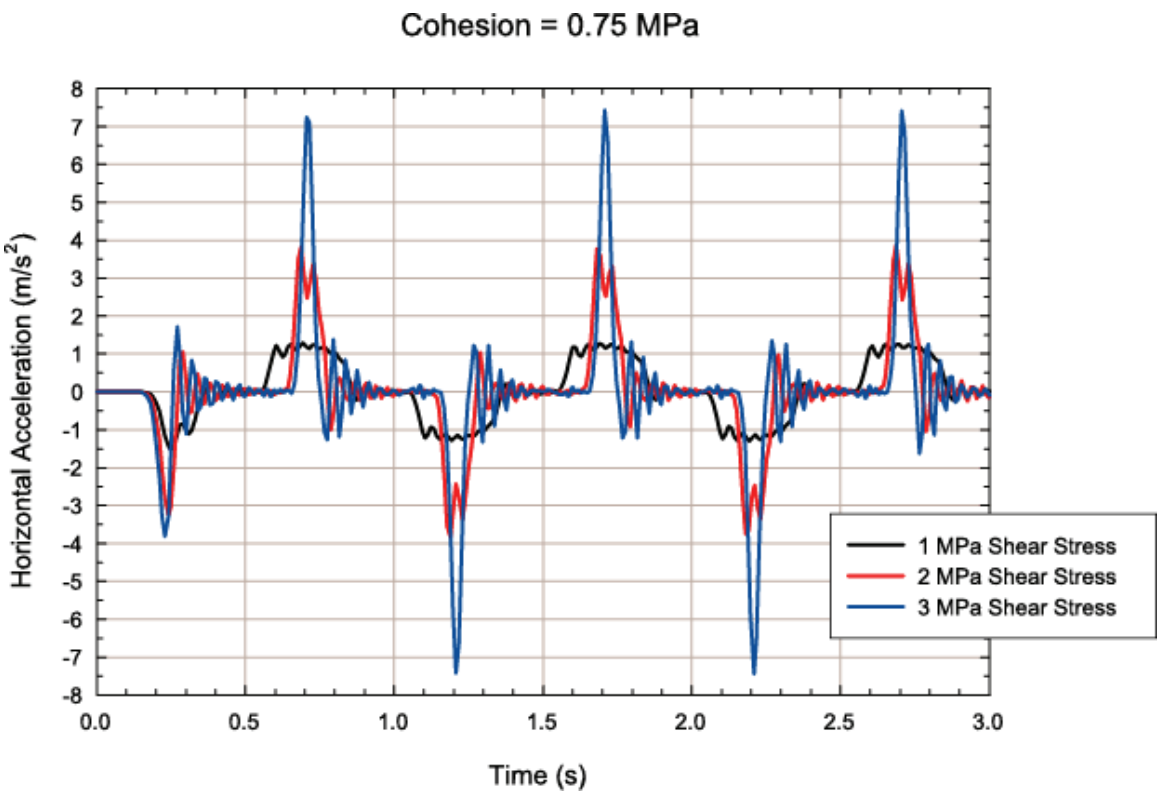

Figure 13. Comparison of acceleration results from ABAQUS/Standard with a cohesion of 0.75 MPa for the thin deformable zone using input shear stress amplitudes of 1, 2, and 3 MPa.

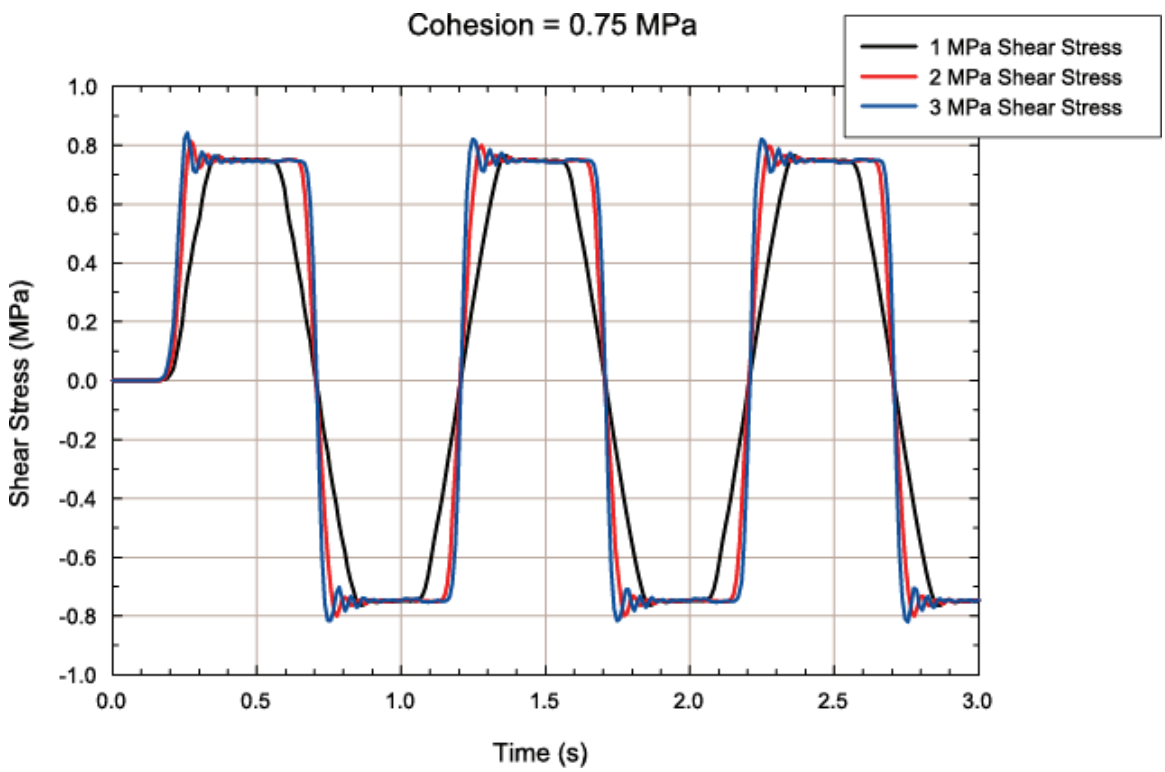

Figure 14. Comparison of shear stress results from ABAQUS/Standard with a cohesion of 0.75 MPa for the thin deformable zone using input shear stress amplitudes of 1, 2, and 3 MPa.

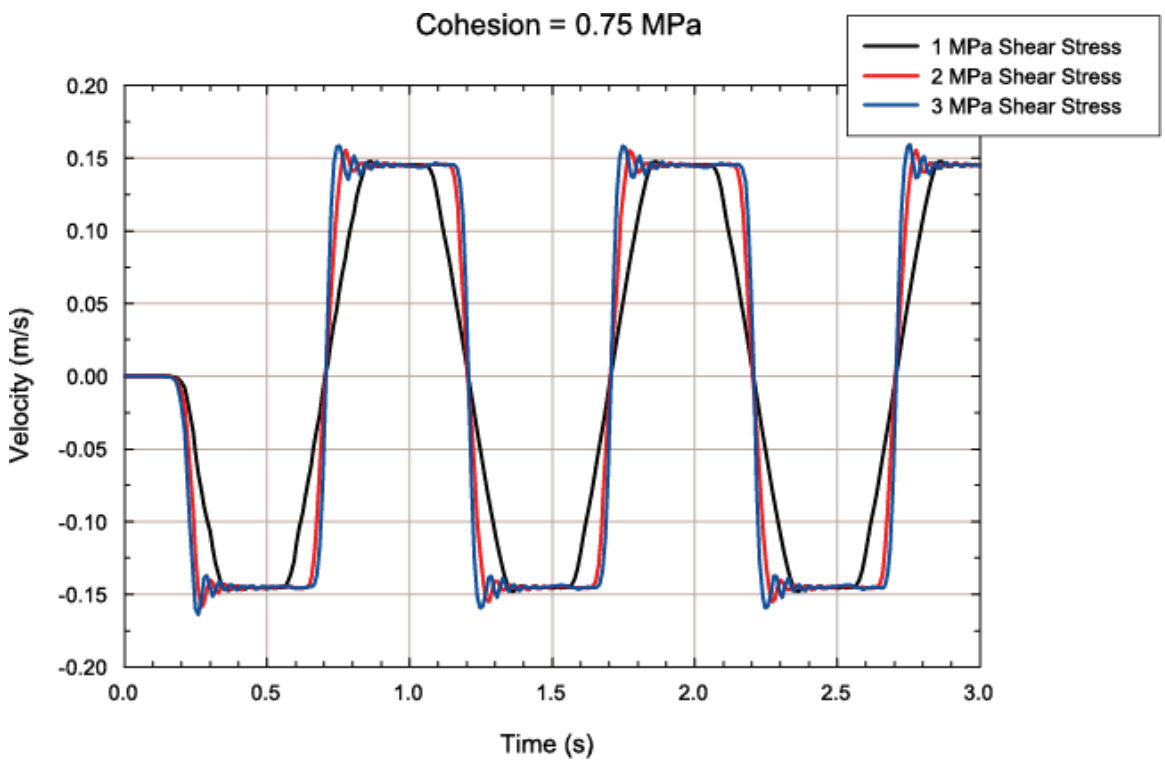

Figure 15. Comparison of velocity results from ABAQUS/Standard with a cohesion of 0.75 MPa for the thin deformable zone using input shear stress amplitudes of 1, 2, and 3 MPa.

DOCUMENTS CITED

Bechtel SAIC Company, LLC. "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada." ANL-MGR-GS-000004, Rev. 00. Las Vegas, Nevada: Bechtel SAIC Company. 2005.

Brady, B.H.G., S.M. Hsiung, and A.H. Chowdhury. "Qualification Studies on the Distinct Element Code UDEC Against Some Benchmark Analytical Problems." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses CNWRA 90-004. 1990.

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Ofoegbu, G.I., A. Ghosh, M.P. Ahola, S. Hsiung, and A.H. Chowdhury. "Evaluation of ABAQUS as a Compliance Determination Computer Code." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses CNWRA 95-016. 1995.

"I have reviewed this scientific notebook and find it in agreement with QAP–001."

Signature