APPENDIX C – DELINEATING PUR INJECTION WITH SURFACE REFRACTION TOMOGRAPHY

"Surface Refraction Tomography (SRT)" is an analytical method for reconstructing subsurface properties using first arrival travel times of seismic energy propagating from surface-located sources through soil/rock materials to surface-mounted receivers. This method allows data from multiple conventional 2D seismic refraction surveys to be processed into one 3D assessment of subsurface conditions. Although somewhat labor intensive, running multiple 2D surveys for 3D volumetric ground imaging is considerably more economical than 3D data acquisition, using standard refraction sources and receivers.

For the South Fork retaining wall investigation, the survey included the ground volume bounded by the roadway shoulder (retained wall fill) and retaining wall structure. Three geophone lines were established within the survey area:

> (1) along the edge of the adjacent roadway approximately 3.7 m (12 ft) from the top edge of the wall,
> (2) along the roadway shoulder approximately 1.8 m (6 ft) from the top edge of the wall, and
> (3) approximately 0.6 m (2 ft) out from the toe of the wall. Each receiver line contained 24, 4.5 Hz, uniaxial plate-mounted geophones spaced on 1.5-m (5-ft) centers.

Four source lines were run for each geophone line:

> (1) along the edge of the roadway approximately 3.7 m (12 ft) from the top edge of the wall,
> (2) along the roadway shoulder approximately 1.8 m (6 ft) from the top edge of the wall,
> (3) along the wall face approximately 1 m (3 ft) above the toe of the wall, and
> (4) approximately 0.6 m (2 ft) out from the toe of the wall.

Each line contained 12 source locations spaced on 3-m (10-ft) centers, generated by a 9.1 kg (20 lb) sledge hammer, totaling 48 sources distributed above, on and below the wall for each geophone line surveyed. A typical source/receiver layout is shown in Figure 26. The surveyed source/receiver array resulted in nearly 3,500 raypaths intersecting the wall structure and retained fill – an adequate coverage within the limits of the investigation.

Each source/receiver pair was mapped to the corresponding seismic signal collected with a Geometrics StrataView seismograph and stored in SEG-2 format. The first arrival times were determined using the GAP-3D automated picking algorithm, developed by Summit Peak Technologies, Inc., Parker, CO. GAP-3D uses a multi-dimensional B-Spline Interpolation Network (BIN) which accounts for waveform shape, source/receiver distance, time, adjacent picks, and filter distortion when automatically determining first arrivals based on user-provided picking examples. This technique provides more consistent picks, is unaffected by fatigue or variations in manual picks, and is more customized to variations in field conditions and filter parameters than other static automatic pickers.

Figure 26. Photo. 2D seismic refraction line layout along roadway edge above retaining wall, including 24-channel "Landstreamer" geophone string and 20-lb triggered sledgehammer seismic source.

Source/receiver arrival times were then used to reconstruct the seismic propagation velocity structure of the wall and retained fill immediate to the wall. The velocity model is constructed using spherical elements of equal radii in a tetrahedral packing structure, connected by links of equal length, depicted in Figure 27. The velocity information is contained within the links to allow for anisotropic conditions. The velocity of each spherical element is obtained by averaging the scalar velocity of the connection links for display purposes.

The model is initialized to a homogeneous average velocity for more consistent, unbiased reconstruction. Seismic waves are propagated through the tetrahedral model structure using wavefront normal vector interpolation, a modified Eikonal method optimized for this structure in terms of efficiency and accuracy. A wave is propagated at each source and receiver in the model to obtain first arrival times at each model element. The arrival times for each source/receiver pair are added to generate a raypath Fresnel region. The Fresnel region is used to correct the model to match arrival time picks, incorporating a rational function proportional to Fresnel density. The resolution is initialized at a low value and incrementally increased for each iteration. This technique improves the reconstructed velocity model in both accuracy and resolution with each iteration.

After inversion, the 3D tomogram was sliced and contoured in both perspective and parallel views for visualization of the velocity structure before and after PUR injection. Difference plots allow volumetric changes to be easily viewed, indicating where in the raypath-defined survey volume changes in ground velocity occurred. As an example, Figure 28 illustrates the velocity difference tomogram obtained from the seismic survey conducted along the wall. Zones within the wall indicating velocity increases greater than 76.25 m/s (250 ft/s) following PUR injection are highlighted as color-coded volumes.

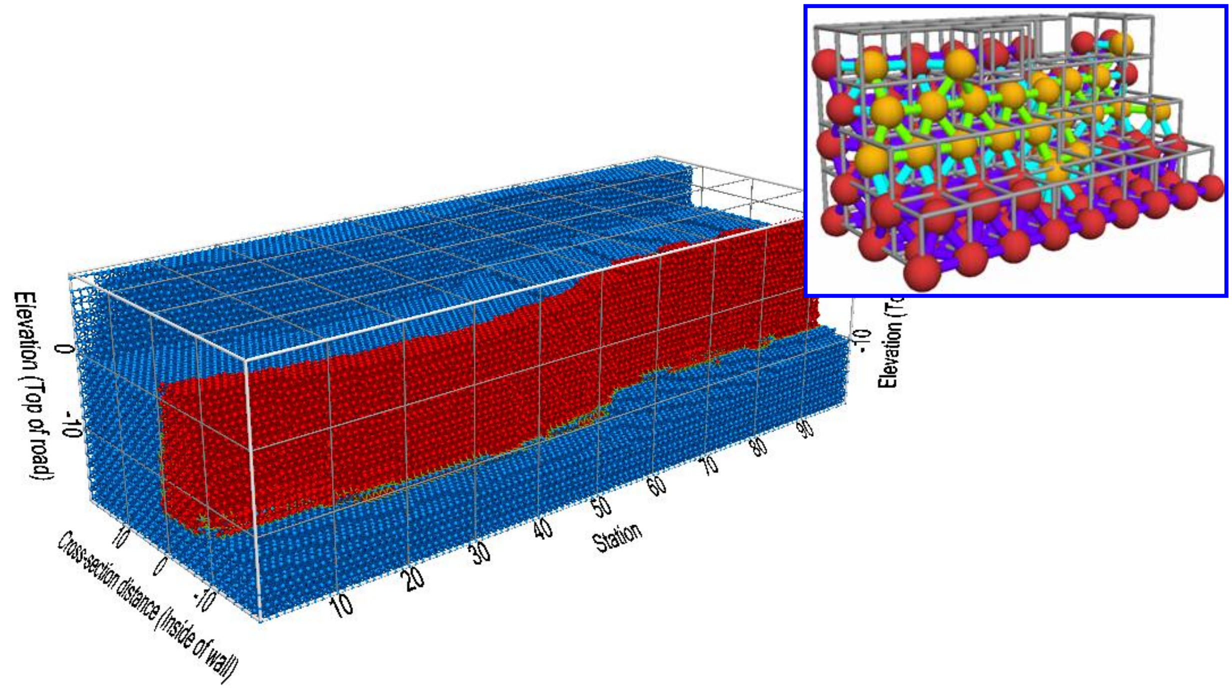

Figure 27. Schematic. Example visualization of the GAP-3D model configuration as applied to a retaining wall evaluation.

The difference tomogram requires some interpretation, since tomography cannot accurately reconstruct low velocity regions. The inversion converges to the maximum velocity that minimizes the error. In the case where a void of 0 m/s (0 ft/s) results in the same arrival times as a low-velocity anomaly of 305 m/s (1000 ft/s), due to ray refraction in higher velocity regions around the void, the tomography will reconstruct the void region as 305 m/s (1000 ft/s) (as if the rays passed slowly through the void). After PUR injection, the increase in subsurface velocity alters the location and shape of Fresnel regions within the structure, even though the source and receiver locations remained unchanged. Therefore, slight apparent decreases in velocity between the before and after tomograms may occur around actual void zones and should be interpreted as resulting from an overall increase in subsurface velocity (the apparent velocity of the void drops with ground improvement). Figure 28 depicts velocity increases within the groundmass; however, the engineer should be aware that, based on the preceding discussion, similar tomograms can be generated that appear to depict apparent softening because of the tomography inversion process – though in reality only ground improvement is actually taking place.

PUR injection at the study site resulted in two distinct resin forms within the wall mass: (1) a low density, stiff, void-filling PUR foam resulting from resin interaction with high moisture contents within the wall mass and retained fill (heavy rains occurred over the days prior to study), and (2) a hard resin product coating the wall rock and strengthening rock-on-rock contacts, but not filling voids (resin stopped foaming once the rain stopped and the wall dried out). Although both of these PUR forms result in significant wall structure strengthening – either due to rock mass consolidation or rock bonding – neither form overwhelmingly influences the velocity structure of

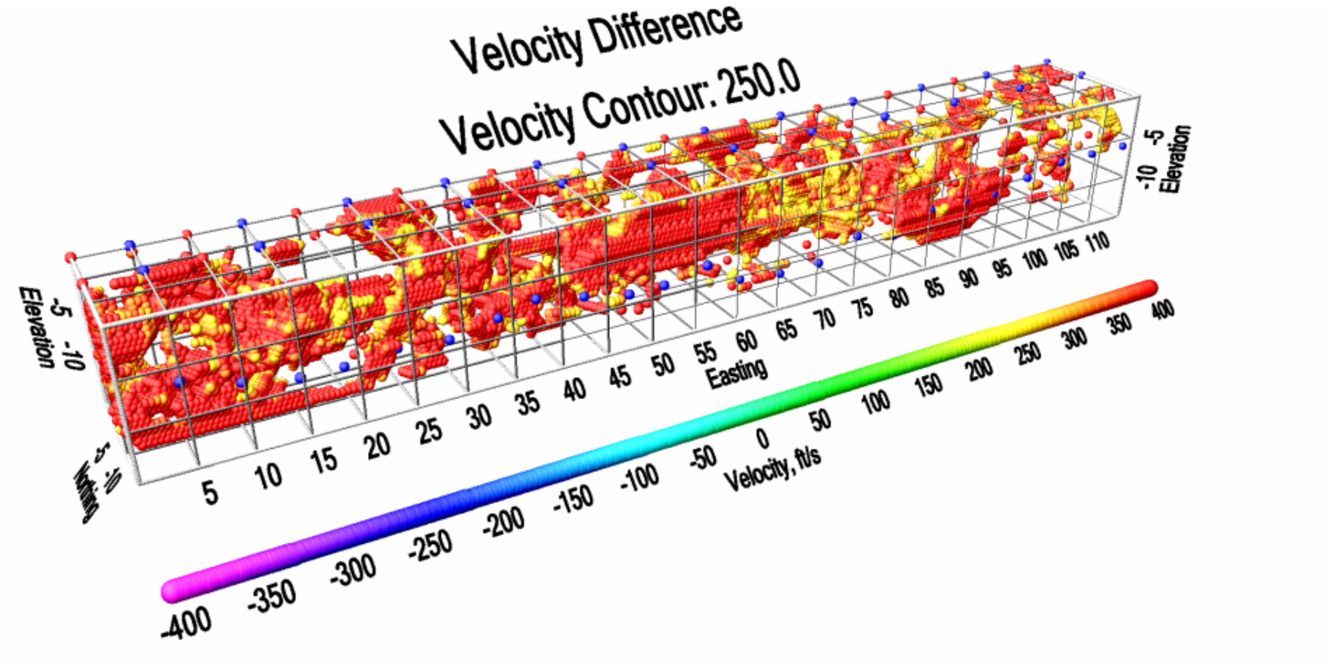

Figure 28. Schematic. Velocity difference tomogram of the surveyed wall volume at the South Fork study site. The red points at the top and bottom of the wall volume represent geophone locations; blue points represent source locations. The highlighted 250+ ft/sec volume is interpreted as representing significant changes in ground conditions resulting from PUR injection.

the wall. The foamed resin product possesses a relatively low velocity, so seismic energy is generally funneled through the stiffer rock-on-rock contacts. The rock mass consolidating effects of the foamed resin greatly increase the confined strength of the wall structure, but does little to change the velocity condition. The hard resin product has a much higher velocity than the foamed resin, but does not fill voids – it only strengthens the rock-on-rock contact zones. As with the foamed resin product, substantial wall structure strength gains are not reflected in significant velocity gains. Therefore, whereas the gross velocity structure of the wall mass prior to PUR injection was on the order of 305 to 610 m/s (1,000 to 2,000 ft/s), only modest gains in structure velocity of 61 to 122 m/s (200 to 400 ft/s) were observed in the velocity difference tomograms.

Despite the low velocity differences between before and after PUR injection surveys, the distribution of velocity gains do generally coincide with PUR injection observations along the wall – PUR follows a path from the installation rod (set back several ft from the top of the wall) to a low exit on the wall face. Additional seismic sources located higher on the wall face would have likely picked up the hand-held face pumping effort conducted along the wall, but the current survey configuration does tend to confirm what was believed to be happening in the field. Figure 29 provides cross-section views of the 3D tomogram at selected locations along the wall illustrating the general trends in velocity gains emanating from surface injection behind the wall.

Overall, SRT was determined to be a good geophysical analysis method for identifying trends in PUR ground improvement based on 3D mapping of modest velocity gains within the wall and

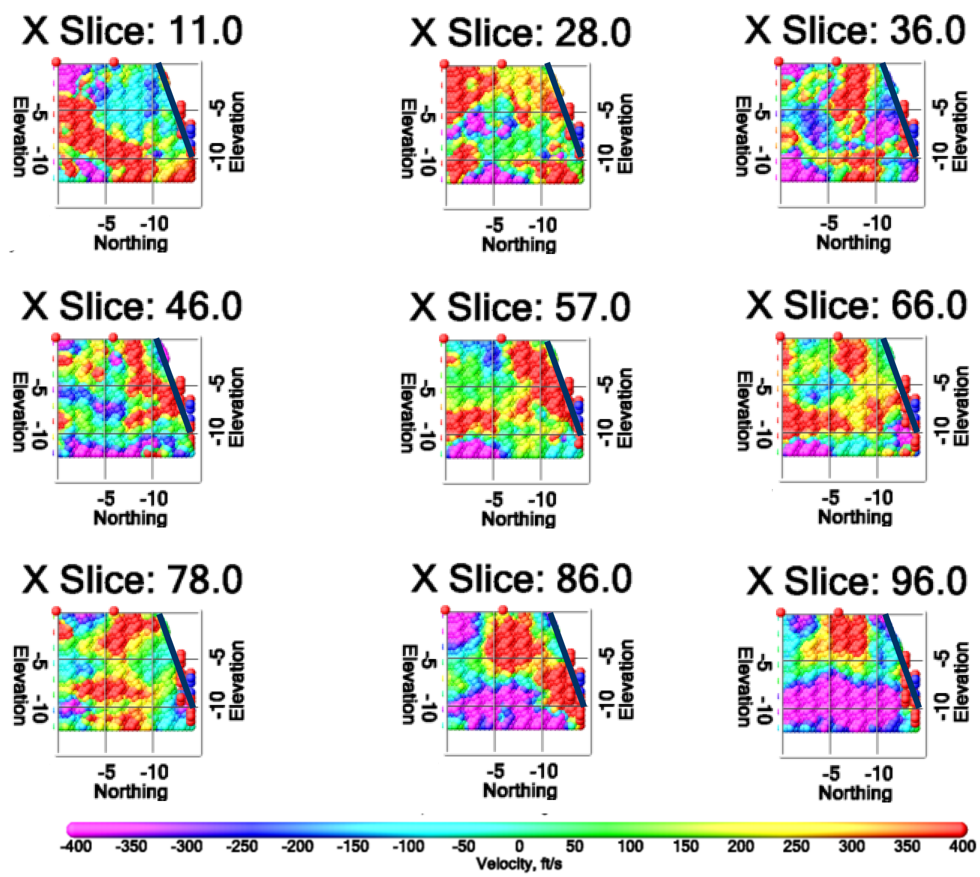

Figure 29. Schematic. Selected velocity difference tomogram cross-sections along the retaining wall (wall face is on the right). Higher velocity changes generally emanate from the ground surface behind the top edge of the wall (coincident with injection rod locations), and migrate toward the more porous wall face – where PUR was routinely seen flowing from the toe to mid-height of the wall.

retained fill structure. A denser and more spatial distribution of seismic sources along the wall face would have certainly yielded better results; however, the current source/receiver array configuration was sufficient to prove the concept and indicate PUR strength and consolidation trends. It should be noted that a ground penetrating radar (GPR) survey was also conducted at this site using 300, 500 and 900 MHz antennas traversed along survey lines at the top of the wall (paralleling the seismic survey lines). Unfortunately, the dielectric contrast between the PUR and groundmass (including loose soils and air-filled voids) was not sufficient to delineate injected PUR volumes. This method could still prove promising and considerably more cost-effective than SRT surveys if a high-dielectric permittivity or conductive material could be effectively added to the PUR to improve the electromagnetic contrast.