REPORT

Characterization of Abandoned Underground Mines with Full Waveform Tomography

Submitted to
Tetra Tech Inc. and
Ohio Department of Transportation

Project Manager
Pete Nix
Tetra Tech
6530 West Campus Oval, Suite 130
New Albany, OH 43054

Principal Investigator
Khiem T. Tran, Ph.D.
Assistant Professor; Clarkson University,
Department of Civil and Environmental Engineering,
Box 5710, Potsdam, NY 13699;

May 2017

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I. INTRODUCTION

Seismic survey is conducted to image underground mine voids under SR 669 just outside of Crooksville, Perry County, Ohio. The test site begins close to the intersection of SR 669 and Twp Rd. 167 and extends for 1200 ft. No mine map has been found for the site. Three mine subsidence features were observed on the hill above the roadway in the northeast quadrant of the intersection. A suspect feature was observed approx. 500 ft east of the intersection, under SR 669. It is believed to be a drift entry with seepage.

Previous borings installed by ODOT at the site revealed:

- Mine working is approximately 15-20 ft below road grade with a 5-6 ft mined seam height. It is assumed that this mine is in that same seem.
- Subsurface profiles consist of layers of silty clay and clay of varying thickness, and a 5 foot or more thick layer of "soft gray shale" shale.
- The boring logs also show coal ranging in thickness from 0.2 ft to 1.7 ft.

Location of the seismic survey line is shown in Figure 1. The total test length is 1200 ft.

Figure 1: Seismic test location (PER-669-9.07-9.21)

II. SEISMIC DATA COLLECTION AND ANALYSIS

A. Data collection

Seismic testing was conducted for one 1200 ft long survey line on SR 669 at Perry County, Ohio (PER-669-9.07-9.21). The seismic data were collected on asphalt pavement using a 24-channel land-streamer and a propelled energy generator (PEG 40 kg) to induce seismic energy as shown in Figure 2. The land-streamer included 24 4.5 Hz vertical geophones equally spaced at 5-ft intervals, and the PEG is attached to a pick-up truck hitch, with a 10 ft source to receiver offset. The whole test system was towed by the truck along the roadway; data were recorded shot by shot (source impact) every 10 ft for a total of 121 shots on a road segment of 1200 ft. The first shot was at location PER-669-9.07 (distance 0), and the last shot (shot 121) was at location PER-669-9.21 (distance 1200 ft).

The main advantage of using land-streamer testing system is that geophones are not required to couple to test materials, and only one source location is used at the end of geophone array (fixed distances to all geophones). Thus the whole test system can be moved along roadway quickly for data acquisition. This helps to mitigate negative impact caused by closing the traffic flow under seismic testing.

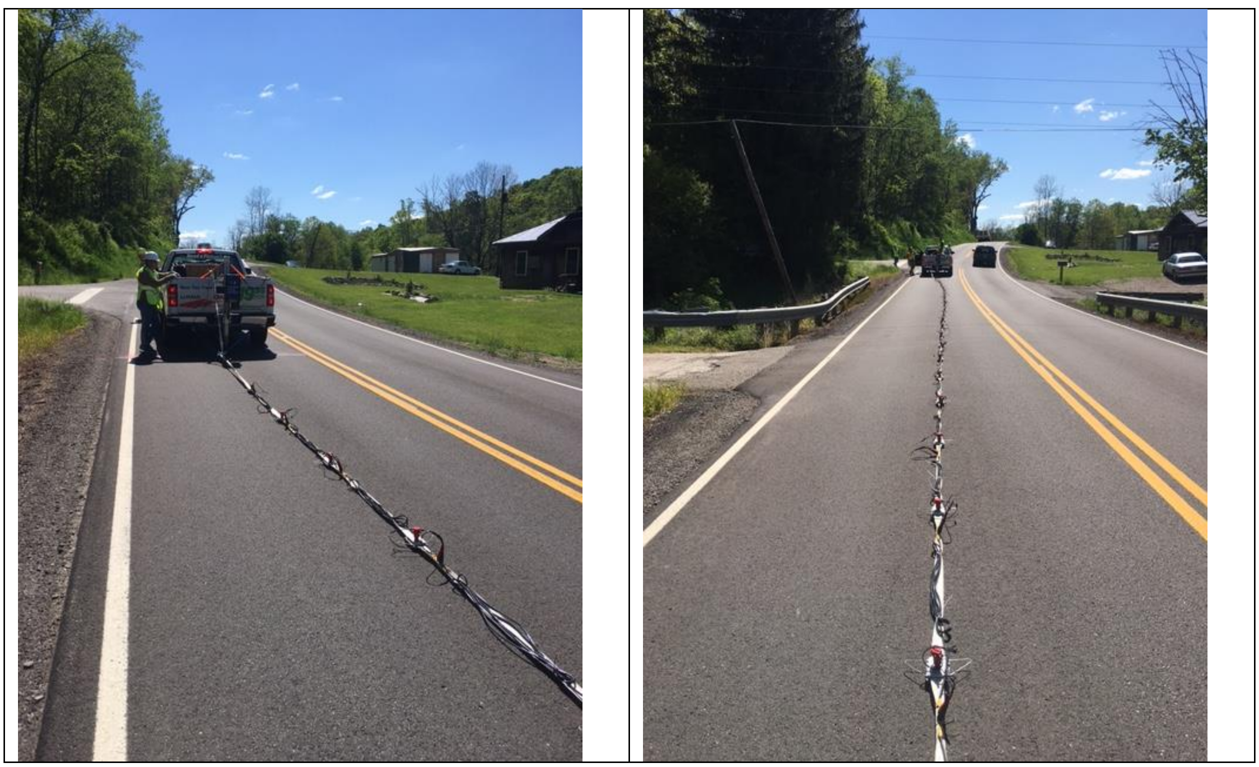
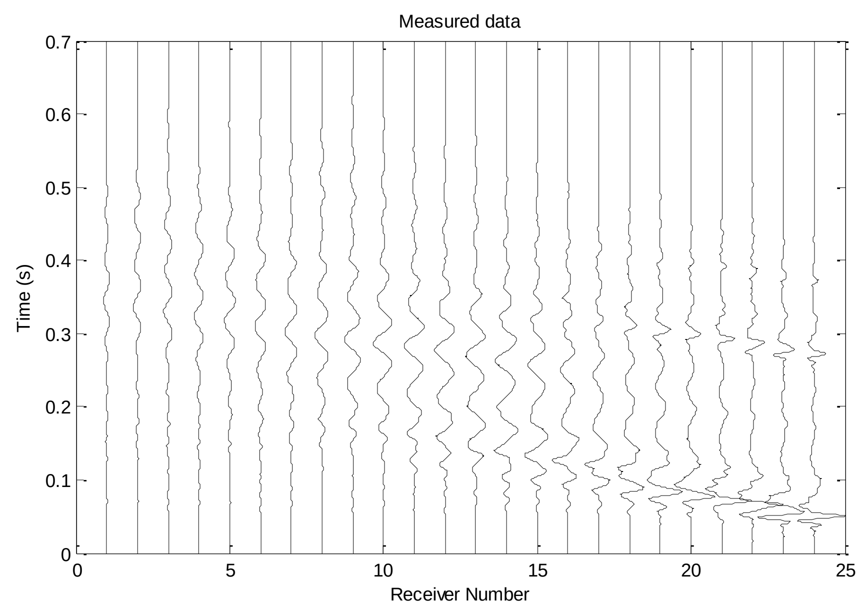


Figure 2: Seismic testing system

B. Data Analysis

All collected seismic data were analyzed by the in-house software based on a recently developed full waveform technique (Sullivan, Tran, and Logston 2016; Tran et al. 2013, Tran and McVay 2012). Two inversion runs were conducted at 2 frequency ranges with the central frequencies of 25 and 40 Hz, beginning from the lower frequency range. Raw collected data (Figure 3a) was low-pass and high-pass filtered to extract data at desired frequency ranges (Figure3b) for analysis.

a) Raw data



b) Filtered data

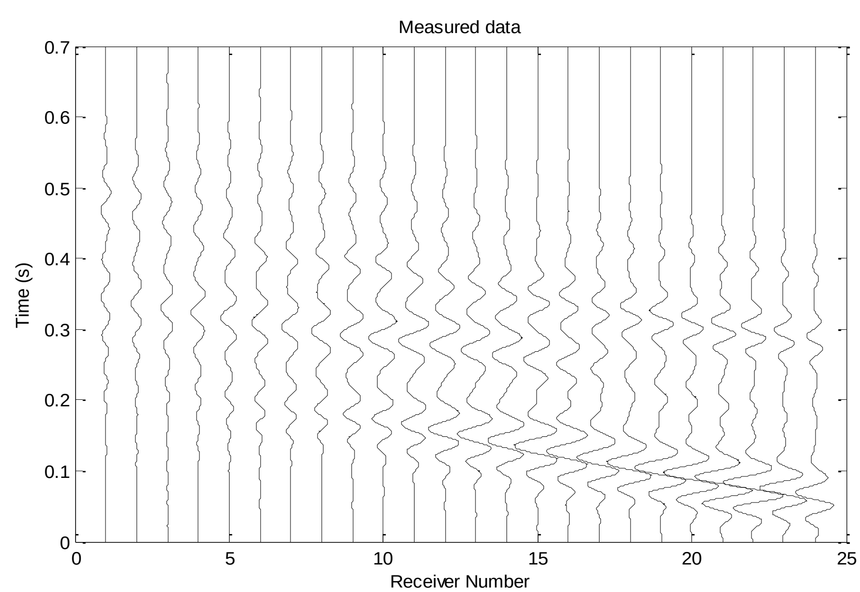


Figure 3: Field recorded data for a sample shot: a) raw data, and b) filtered data

The medium of 40 ft (depth) × 1200 ft (distance) was divided into 7680 cells of 2.5 ft × 2.5 ft. During the inversion (analysis), S-wave and P-wave velocities of cells were updated independently, and each run was stopped when the observed waveform data and the estimated waveform data were similar. As an example, the measured waveforms (field data), the estimated surface waveforms, and residuals (difference between measured and estimated) associated with the final inverted model are shown horizontally in Figure 4 for three sample shots. As evident, the measured and estimated waveform data were very similar across the entire range of offsets, and the residuals were small.

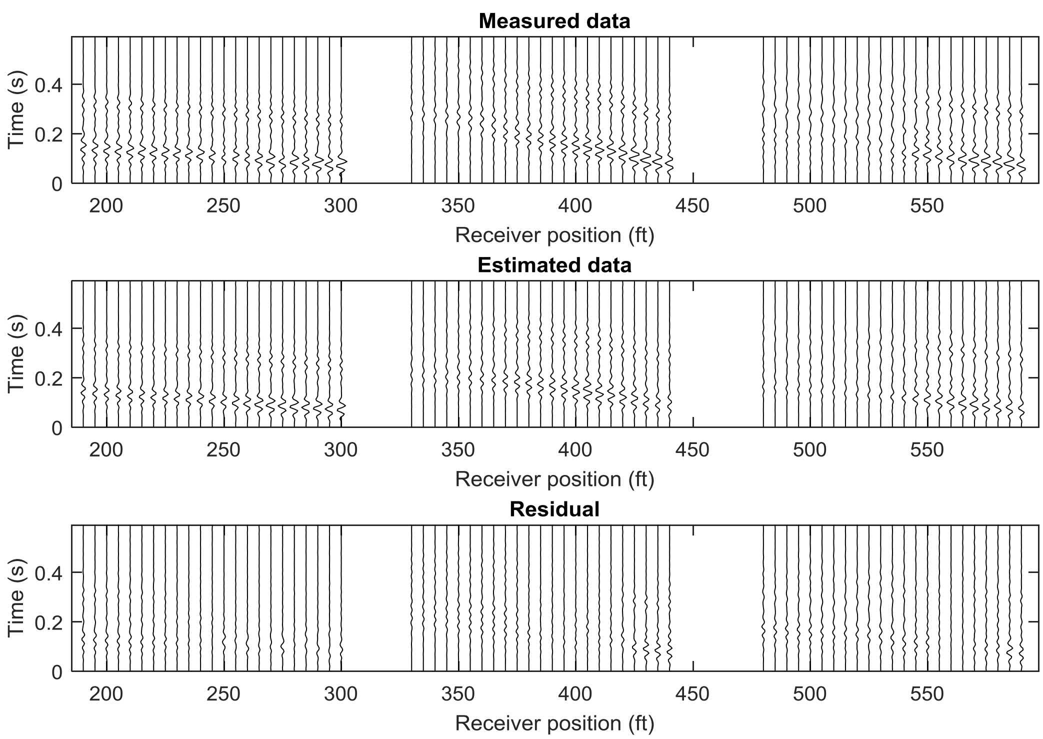


Figure 4: Comparison between measured data and estimated data for shots 30, 45, and 60 (left to right). Residual is the difference between the measured and estimated data.

III. RESULTS AND INTERPRETATION

Figures 5 to 8 show the results of the seismic survey from distance 0 to 1200 ft. **It is noted that the seismic results are the subsurface profile at the center of the traffic lane (not at the shoulder), and distance 0 is exactly at location PER-669-9.07.**

For each figure, the top plot is shear-wave velocity (S-wave), and the bottom plot is compression wave velocity (P-wave). The S-wave and P-wave velocity profiles were determined independently and simultaneously from the analysis of measured data. Generally, the S-wave profiles are more credible than P-wave profiles as the shear waves are less sensitive to traffic noise and water content. Voids can be characterized with S-wave velocity less than 500 ft/s, and P-wave velocity of 1000-1200 ft/s for those filled with air or 4000-4500 ft/s for those filled with water, respectively. Several anomalies are identified in the S-wave velocity, but not seen in the P-wave velocity because they are saturated.

Figure 5 shows the wave velocity profiles from distance 0 to 300 ft. Two anomalies are identified at distances of 40 ft and 250 ft (depth of 15 ft). With the S-wave velocity of about 500-600 ft/s, they may be collapsed mine workings, voids filled with raveled soils and water, or saturated soft embedded clay. No open voids are expected.

Figure 6 shows the wave velocity profiles from distance 300 to 600 ft. A big anomaly is identified at distance of 465 ft (depth of 25 ft). With the S-wave velocity of about 500 ft/s, the anomaly could be an open void or a void filled with raveled soil. Two other smaller anomalies are at distances of 380 ft and 425 ft.

Figure 7 shows the wave velocity profiles from distance 600 to 900 ft. A big anomaly is identified at distance of 645 ft (depth of 18 ft). The S-wave velocity is very low at about 200 ft/s, the anomaly is expected to be an open void. Three other anomalies are identified at distance of 725 ft (depth of 35 ft), distance of 790 ft (depth of 35 ft), and distance of 820 ft (depth 15 ft). As S-wave velocities of these anomalies vary from 500 to 600 ft/s, they may be collapsed voids or just interbedded clay in rocks.

Figure 8 shows the wave velocity profiles from distance 900 to 1200 ft. Two anomalies are identified at distance of 1120 ft (depth of 20 ft), distance of 1175 ft (depth of 30 ft). S-wave velocities of these anomalies are about 600 to 700 ft/s, they are not open voids.

IV. SUMMARY

Full waveform tomography was used to image underground mine voids under SR 669, Perry County, Ohio. The seismic results reveal several low-velocity anomalies the center of the traffic lane; suggesting both open and collapsed mine voids. Based on the results, it is recommended the following boring locations for verification and further investigation of mine voids:

Primary borings at distances of 465 ft and 645 ft
Secondary borings at distances of 50 ft, 250 ft, 380 ft, 425 ft, 725 ft, 790 ft, 820 ft, 1120 ft, 1175 ft

The primary borings are for locations with expected open voids and secondary borings are for locations with expected collapsed voids or interbedded soft clay. Due to traffic noise, the characterized results may not be 100% accurate. The sizes of the identified anomalies may be 20 - 30% difference from their actual sizes. Also because of the uneven surface elevation, the predicted depths of the anomalies may be a few feet off.

REFERENCES

Sullivan B., Tran K.T, and Logston B. (2016), "Characterization of Abandoned Mine Voids Under Roadway Using Land-streamer Seismic Waves", *Journal of Transportation Research Board*, Vol. 2580, pp. 71-79.

Tran K.T., McVay. M., Faraone M., and Horhota D. (2013), Sinkhole Detection Using 2-D Full Seismic Waveform Tomography: *Geophysics,* 78 (5), R175–R183.

Tran K. T. and McVay M. (2012), Site Characterization Using Gauss-Newton Inversion of 2-D Full Seismic Waveform in Time Domain: *Soil Dynamics and Earthquake Engineering*; 43: 16-24.

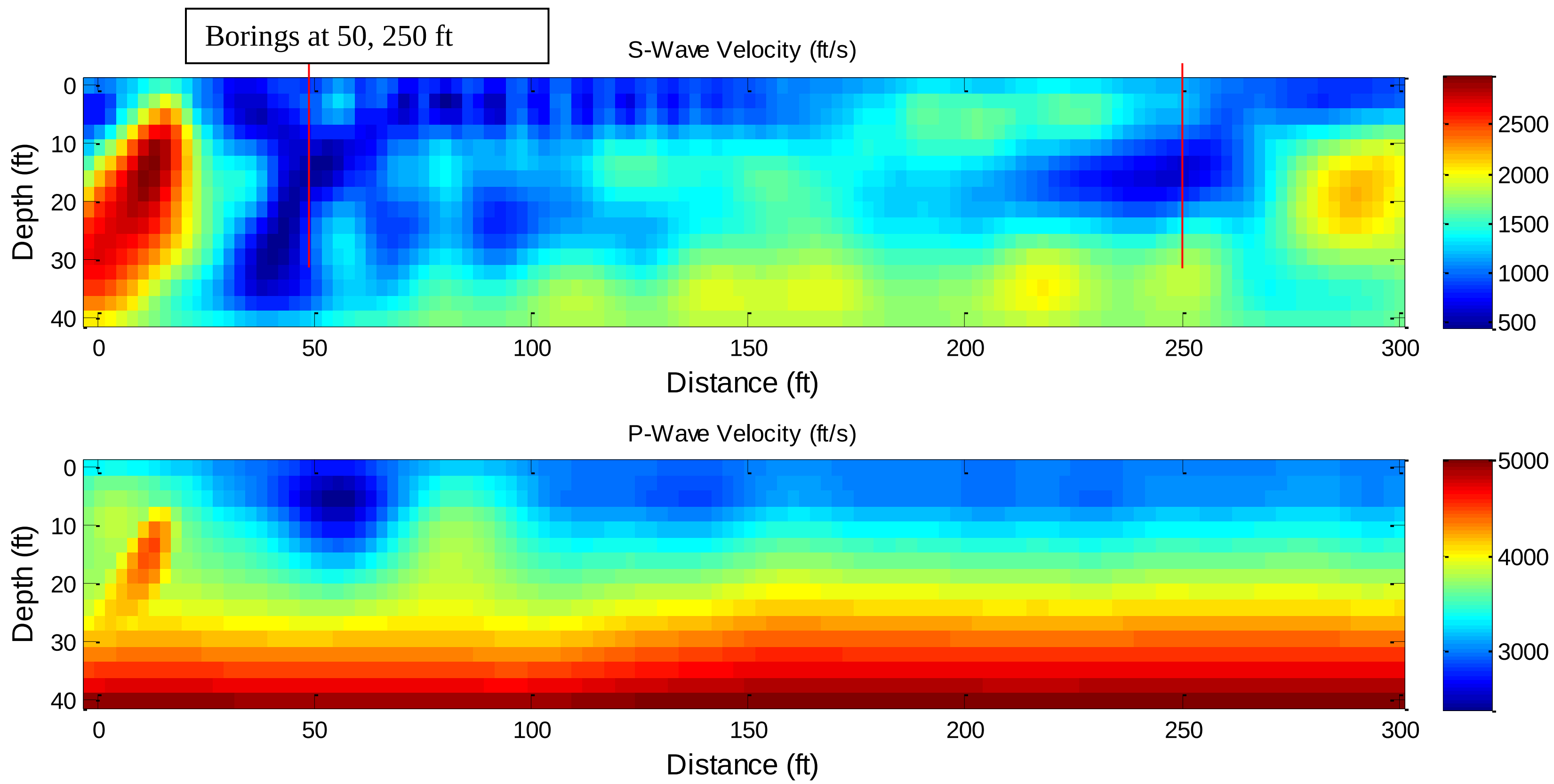


Figure 5: Shear wave and Compression wave velocity distribution: distance 0 to 300 feet **(distance 0 is at PER-669-9.07)**

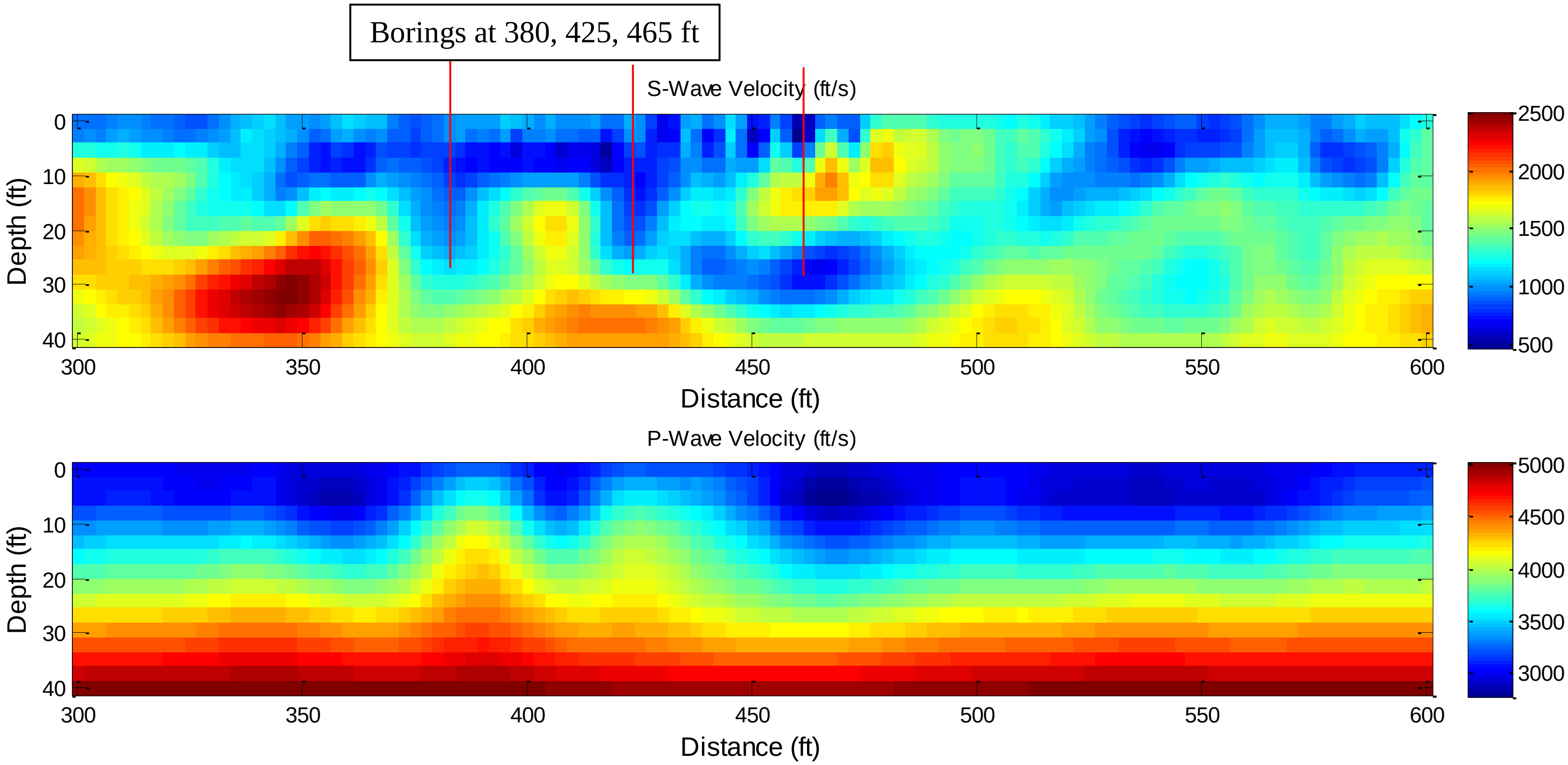


Figure 6: Shear wave and Compression wave velocity distribution: distance 300 to 600 feet

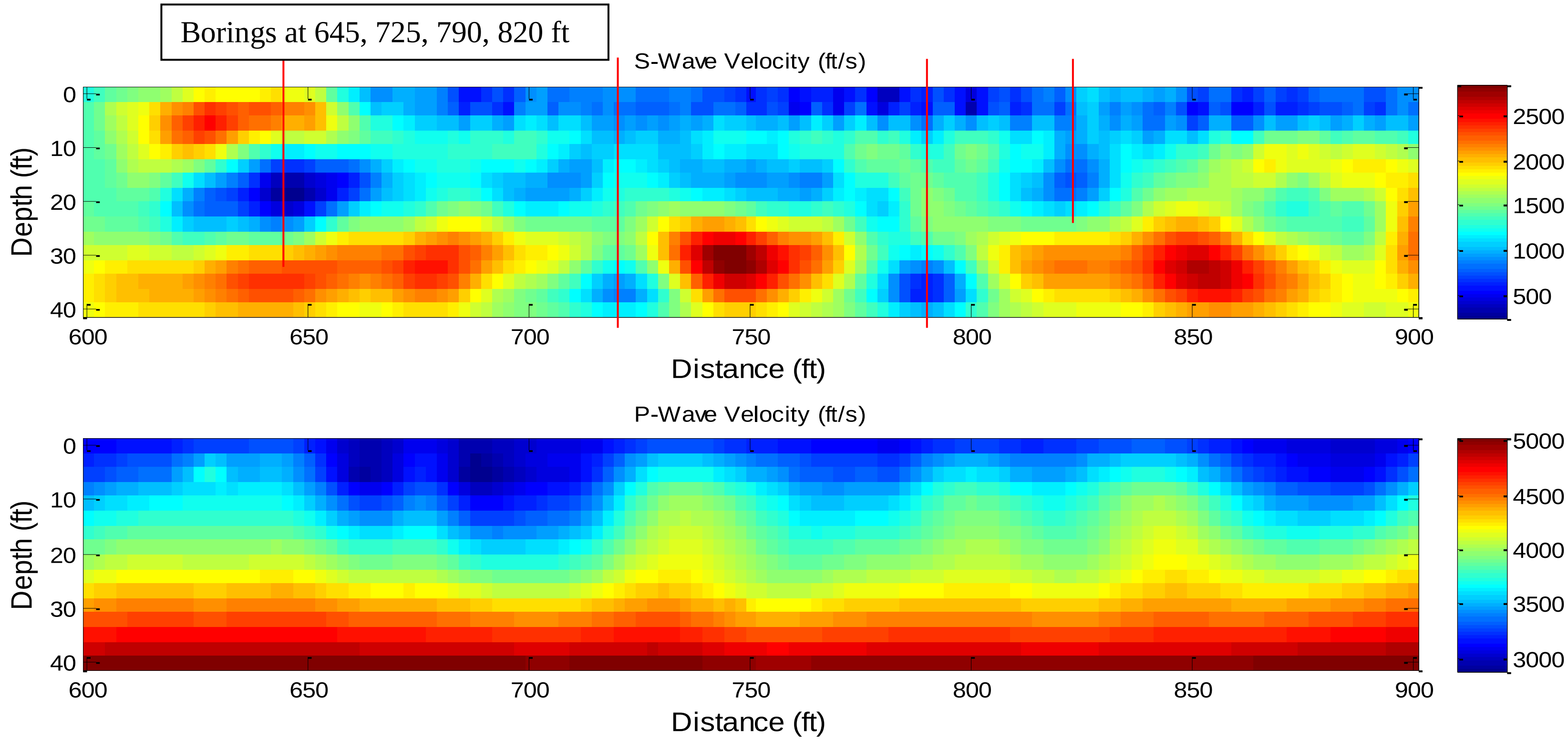


Figure 7: Shear wave and Compression wave velocity distribution: distance 600 to 900 feet

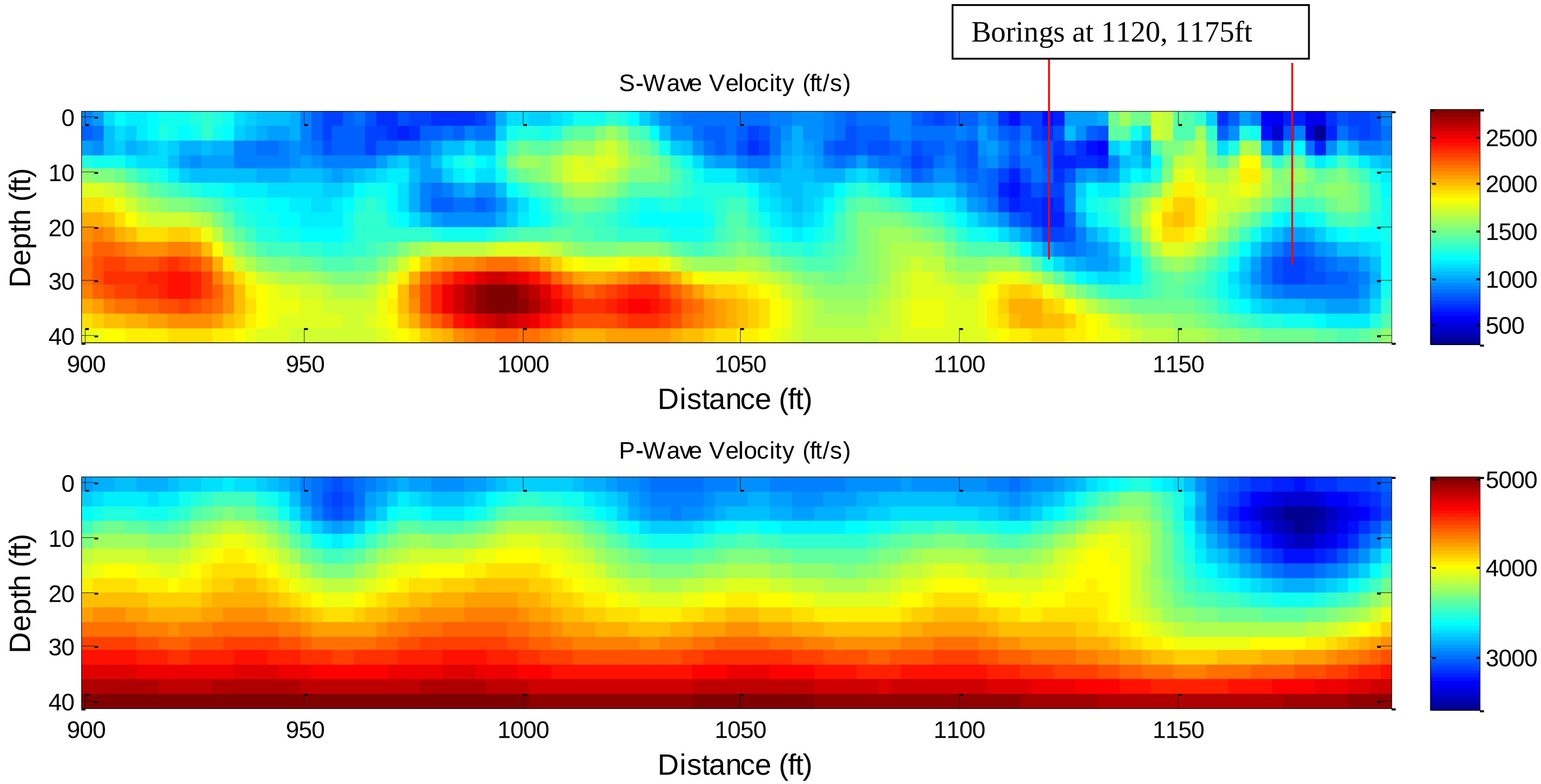


Figure 8: Shear wave and Compression wave velocity distribution: distance 900 to 1200 feet