Imaging Piles in Bridge Foundations Using Tomography and Horizontal Seismic Reflector Tracing

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ABSTRACT

A large number of aging bridges require a reliable inspection of their condition to determine if they are safe, or if they need to be rehabilitated or replaced. The direct assessment of foundations for existing structures would require excavation or, at least, an extensive drilling program. Such an effort would be extremely costly and impractical. It could also compromise the integrity and stability of the structure itself. The authors present the inspection technique that combines seismic cross-hole tomography and 3D imaging of seismic reflectors. The measurements are conducted using three drill holes that surround the investigated underground foundation components. The technique produces images of piles or other structural features through triangulation of reflected waves recorded at several points along each of drill holes.

The authors also recognize new challenges when imaging a cluster of piles in a soft ground due to a need for seismic waves of the proper wavelength, and due to an intense dispersion of seismic waves in the space between the piles.

INTRODUCTION

This paper presents the results of investigating substructure foundations at selected locations for a viaduct in Pittsburgh area. The pile foundations were investigated at three locations, one at each abutment, and one approximately in the middle of the viaduct span. The piles were predrilled concrete piles, 0.5 m in diameter each, with no steel reinforcement. At each location there was a different pattern of piles.

The ground at the survey sites was mostly silty to clayey gravel, changing with depth into silty to sandy clay. This type deposit was approximately 18 m thick at Abutment A and around the Middle Pedestal, and thinning to nearly 6 m at the opposite Abutment B. The softer ground deposits were underlain by claystone/sandstone bedrock layers.

SURVEY OUTLINE

Three boreholes were drilled around each site (Figure 1). At each site, two holes were located on the same side outside the foundation perimeter, and the third

hole was located on the opposite side across the bulk of the foundation piles. The holes were drilled down to around 3 m into a more competent rock that required switching to a drill bit to continue drilling. The holes were cased with a PVC pipe. The bottom of each PVC pipe was capped to hold water. The annulus for each hole was grouted with cement-based rigid grout.

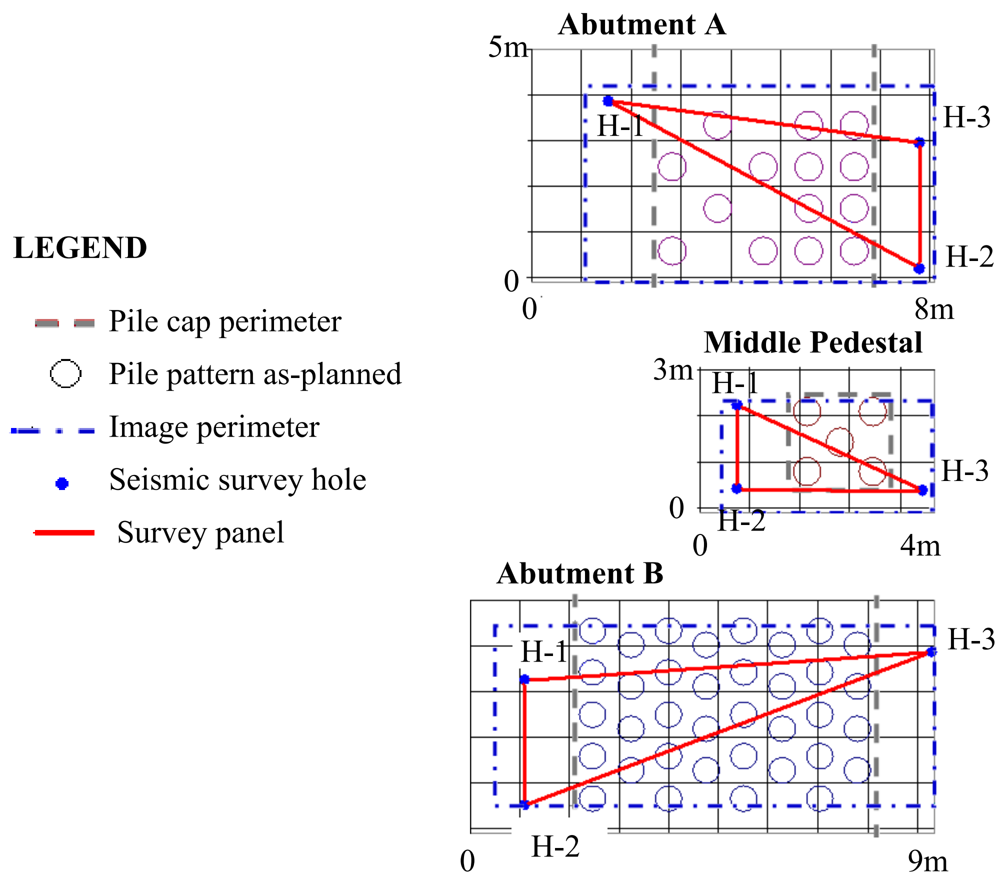

Figure 1. Survey layout at sites selected for geophysical investigation of the viaduct foundations.

EQUIPMENT

A highly repeatable swept-frequency sesmic source was lowered to different depths in selected water-filled boreholes. The water in each borehole transferred seismic energy from source to the ground.

A string of 12 hydrophones at 2 m centers were lowered into a neighboring water-filled hole for detecting seismic waves coming from the source and converting them to measurable electric signals. These electric signals were acquired by a digital multi-channel seismograph and were saved as seismic records. Each recording was activated when the source was triggered.

METHODOLOGY

Two seismic methods were combined to image the cluster of piles at each site (Descour *et al*, 2006):

1. *Seismic Velocity Tomography* was used primarily to build the general velocity model for each site;
2. *Single Hole Reflector Tracing* was used for imaging piles in the cluster by transposing waves reflected from individual piles back to their origin. In the process the velocity model from the tomography was used to convert wave travel time to distance;

Seismic Velocity Tomography

Seismic velocity tomography uses the inversion of travel times for seismic waves that travelled between known points (trans-illumination) to reconstruct the velocity model of the ground as an image of the ground features. The reconstruction is digital in nature, and is accomplished by converting the surveyed volume into a grid of uniformly spaced nodal points forming an orthorhombic lattice. The spacing between the closest nodal points defines resolution of the reconstruction in each direction.

Furthermore, the reliability and resolution of reconstructed seismic velocity models are determined by the geometry and the number of seismic sources and receivers which in turn define the density of coverage, and the length of raypaths. More detailed discussion of this subject can be found in Descour *et al*. (2006).

For a cross-hole tomography survey a simple analysis of the average velocity profiles for each par of holes provides an initial velocity model for the tomographic inversion. This model helps reducing the effect of missing coverage at the top and bottom of any cross-hole tomographic survey.

For this investigation the cross-hole seismic velocity tomography survey was conducted along panels between each of the three pairs of boreholes (Figure 1) at each survey site. The configuration of boreholes was designed to compare the “original” seismic velocity profile outside the perimeter of the piles, and the velocity profiles crossing and affected by the cluster of piles. For each panel the source was lowered into one (source) hole and was triggered at selected depths to send seismic energy into the ground. A string of hydrophones lowered to the proper depth in the other (receiver) hole measured seismic waves coming from the source.

Each source - receiver pair produced a record of seismic waves coming from the source, and passing by the receiver. In each record the direct seismic waves (P-waves arriving first at each hydrophone) contained information about the velocity structure along their path.

The travel times measured for the direct waves were used to generate 3D velocity tomogram (velocity model) within a rectangular block in the ground. The blocks were sized to include all three panels per surveyed site (Figure 1). The velocity model provided an outline of the ground properties within the block, including some expression of the piles located near individual panels. Most importantly, these velocity models were applied to image piles using the reflected waves (the second technique).

Single-Hole Reflector Tracing

The Single Hole Reflector Tracing technique utilizes contrasts in seismic impedance (product of wave velocity and natural density) that occur at boundaries between the original ground and the piles or other seismic anomalies. Due to that contrast, the piles reflect some of the incoming seismic energy. The strength of reflected waves is proportional to the reflection coefficient R (Waters, 1978; Aki *et al*, 1980) defined as:

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

where: ρ_1 and V_1 are respectively the natural density and wave velocity in the ground, and ρ_2 and V_2 are the natural density and wave velocity in the piles.

The strength of reflected waves also depends on incidence angle of seismic energy. Therefore the reflected waves arriving at the hydrophones are much weaker then the direct waves, and are often difficult to identify visually. However they arrive with a sufficient delay which makes it easier to enhance them by filtering the direct waves off.

The anomalies reflecting seismic waves can be imaged by transposing time records of these waves back to the location of their origin, using the proper velocity model to convert time to distance (Ashida, 1993, 2001, Neil *et al*, 1999). For each pair of seismic source and receiver the locus of all possible reflector positions for the same two-way (source-reflector-receiver) travel time defines ellipsoidal surface in three-dimensional space (Figure 2). For the proper velocity model the transposed reflected signals match in phase at the reflector (pile) location forming a wave-like anomaly.

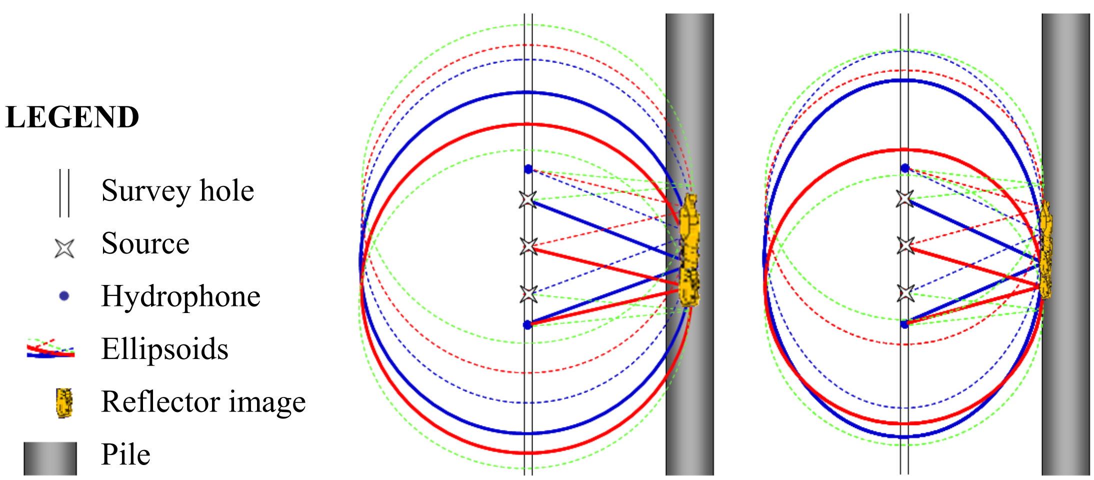

Figure 2.Transposing reflected waves onto the reflector for long waves (left), and for short waves (right).

When conducting the Single Hole Reflector Tracing survey, the source and the hydrophones were placed together in the same borehole. Then the source was

activated at three levels between two neighboring hydrophones (Figure 3). Each source occurrence did send seismic energy through the ground in every direction. The reflected waves returning from the piles were recorded by the hydrophones. Subsequently, the hydrophones were moved by 1 m to the next elevation, and the source was activated at three levels again producing three additional records of reflected seismic waves.

This type of survey was repeated in two remaining holes to allow triangulation necessary for the unique definition of detected piles. The acquired seismic records were processed to generate 3D reflectograms within the volume of each site including structural features of the surveyed pile foundations.

SURVEY RESULTS

Seismic Velocity Model

The analysis of the velocity profiles for panels outside of the perimeter and across the pile clusters confirmed that the presence of piles significantly alters the average velocity in the ground (Figure 3).

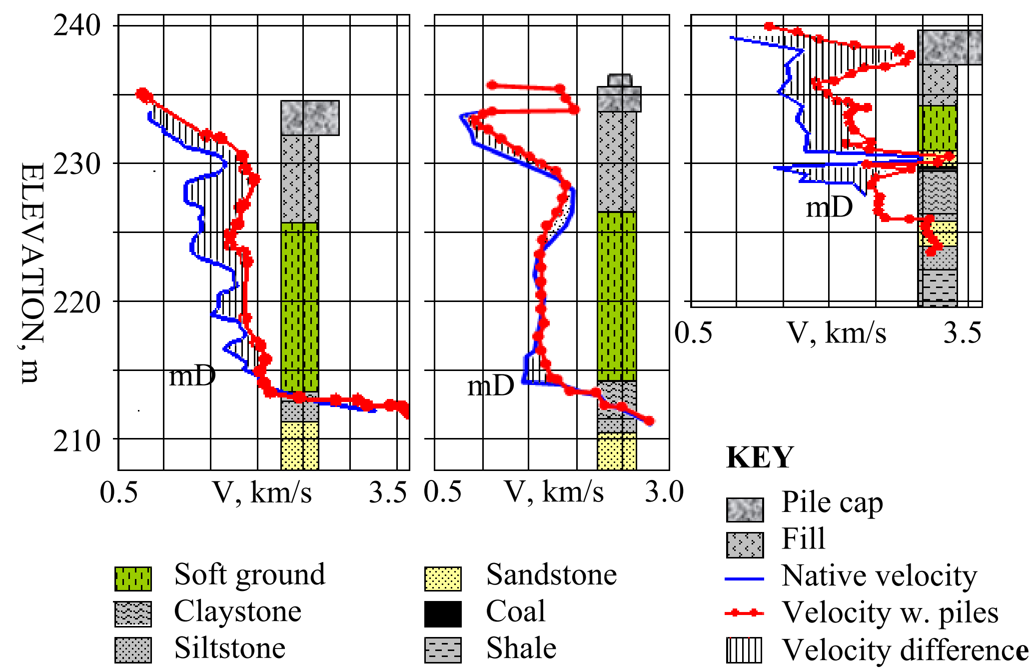

Figure 3. Velocity profiles in native ground near piles, and velocity across the pile clusters, minimum depth (mD), and general geological profiles for all ites.

The concrete piles in a softer ground produced elevated velocity anomalies compared to undisturbed ground conditions. In general, the difference was proportional to the density of pile patterns. And no obvious change could be measured for parts of the ground which properties were similar to the piles. This analysis also indicated the minimum depth (mD) of the pile clusters (Figure 3).

The velocity profiles were used to define initial velocity models for tomographic inversion at each site (Figure 4). The initial velocity models provided additional constraint at the top and bottom parts of the cross-hole 3D tomograms thus improving the final velocity models generated for each site.

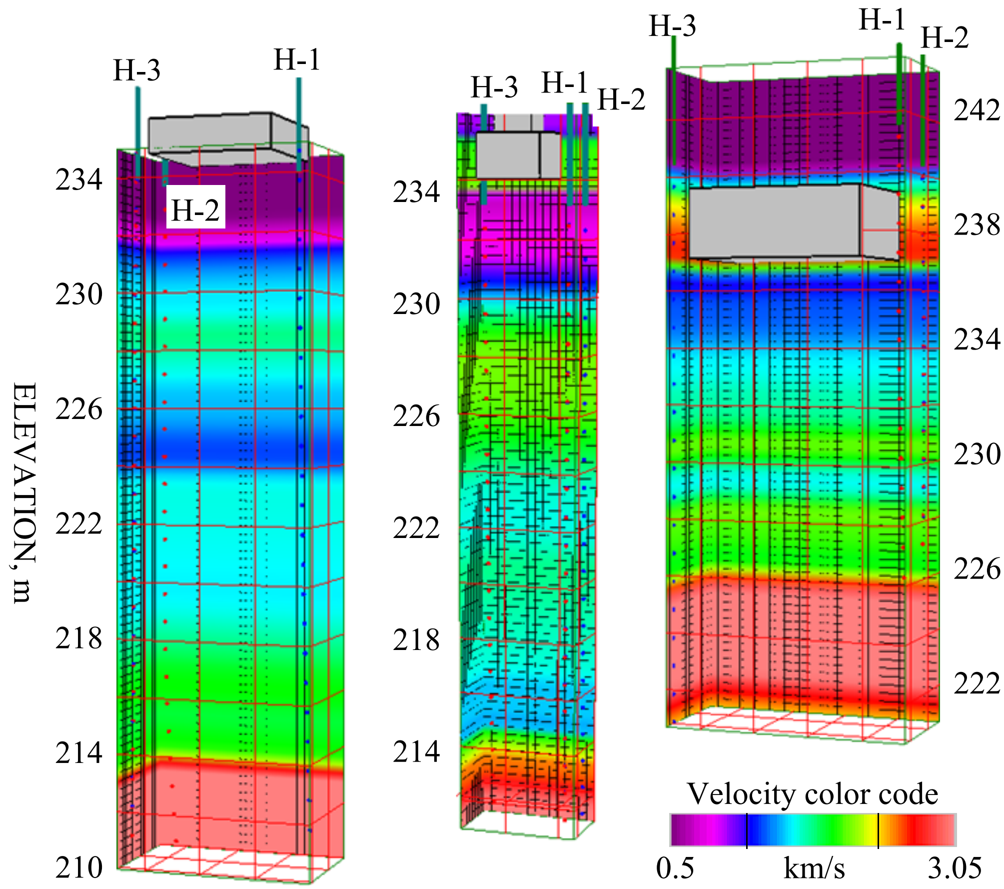

Figure 4. The velocity models for starting tomographic inversion were derived from Figure 3 for Abutment A (left), Middle Pedestal (center) and Abutment B (right).

The resulting 3D contour velocity models (Figure 5) show the tendency for the tomography to “fuse” the multi-pile structure into a larger monolithic feature.
A number of horizontal voids in the velocity images match the lower velocity zones that are not displayed in order to expose pile related features protruding from higher velocity grounds. These spikes and necks are associated with piles that guide seismic energy from higher to lower velocity ground and vice versa. Those are mostly the piles that are closer to the path of seismic waves travelling between “source” and “receiver” holes.

Based on the 3D contour velocity models from the tomographic inversion, it can be safely concluded that the tips of the piles are below the elevation of the lowest “spikes” or “necks”.

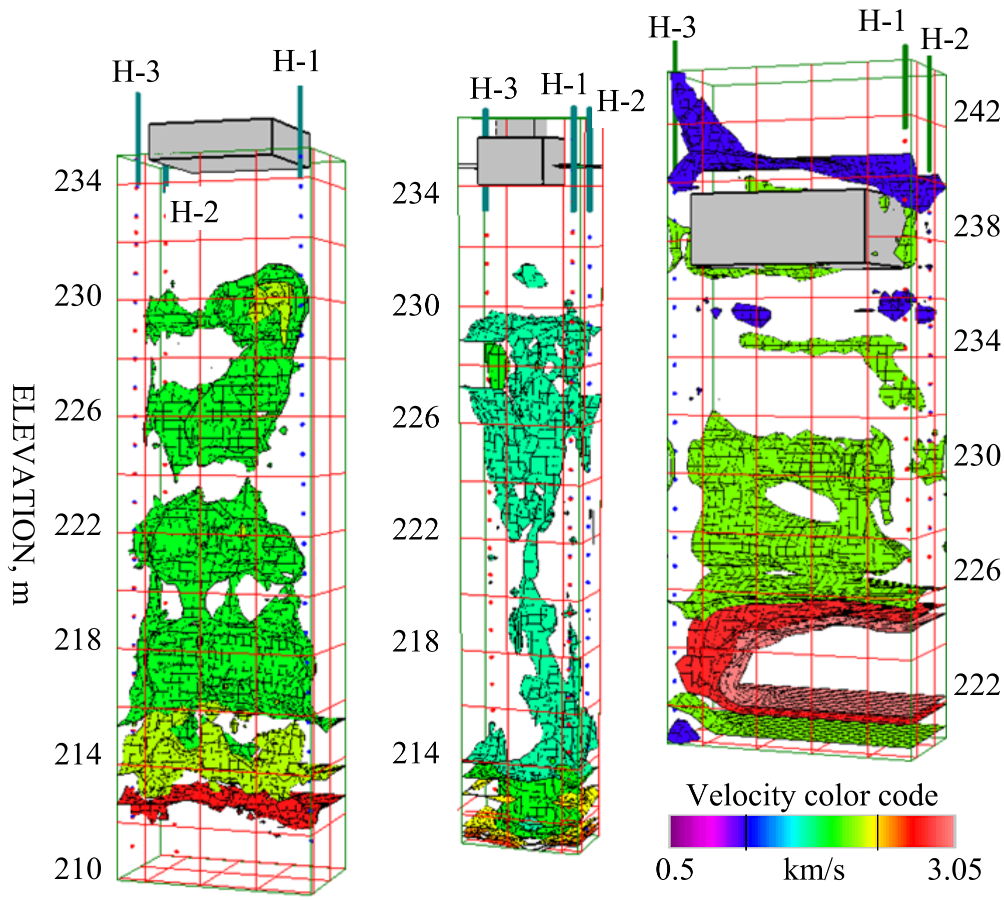

Figure 5. 3D velocity models from tomographic reconstruction for Abutment A (left), Middle Pedestal (center), and Abutment B (right).

Seismic Reflectors

The velocity models generated by the tomographic inversion were included as part of data processing to convert records of reflected waves into images of anomalies within the 3D volume of the imaging block for each site.

Because of changing attenuation of seismic waves with elevation, the images of pile related anomalies for each site (Figure 6) were generated as a sequence of overlapping vertical segments. The elevation range for each segment was defined to include three source-hydrophone sets (as defined in METHODOLOGY) in matching elevation range, one set in each of three survey holes per surveyed site.

Of all three reflectograms in Figure 6 only reflectogram for Abutment A appears distorted at elevation range from 224 to 231.5 m. Also there are gaps from 215 to 216.5 m, from 222.5 to 224.5 m, and from 231.5 m to the bottom of the pile cap.

However, the comparison between the velocity profile across the piles, and alongside the piles for Abutment A in Figure 3 indicates a strong and relatively uniform effect of piles on the ground properties at those elevations. At the same time both the initial velocity profile in Figure 4, and the 3D velocity model in Figure 5

indicate consistent changes in the ground at these elevation. This leads to a conclusion that the perturbations in the pile image in Figure 6 are most likely caused by velocity and attenuation changes insufficiently represented by the 3D velocity model.

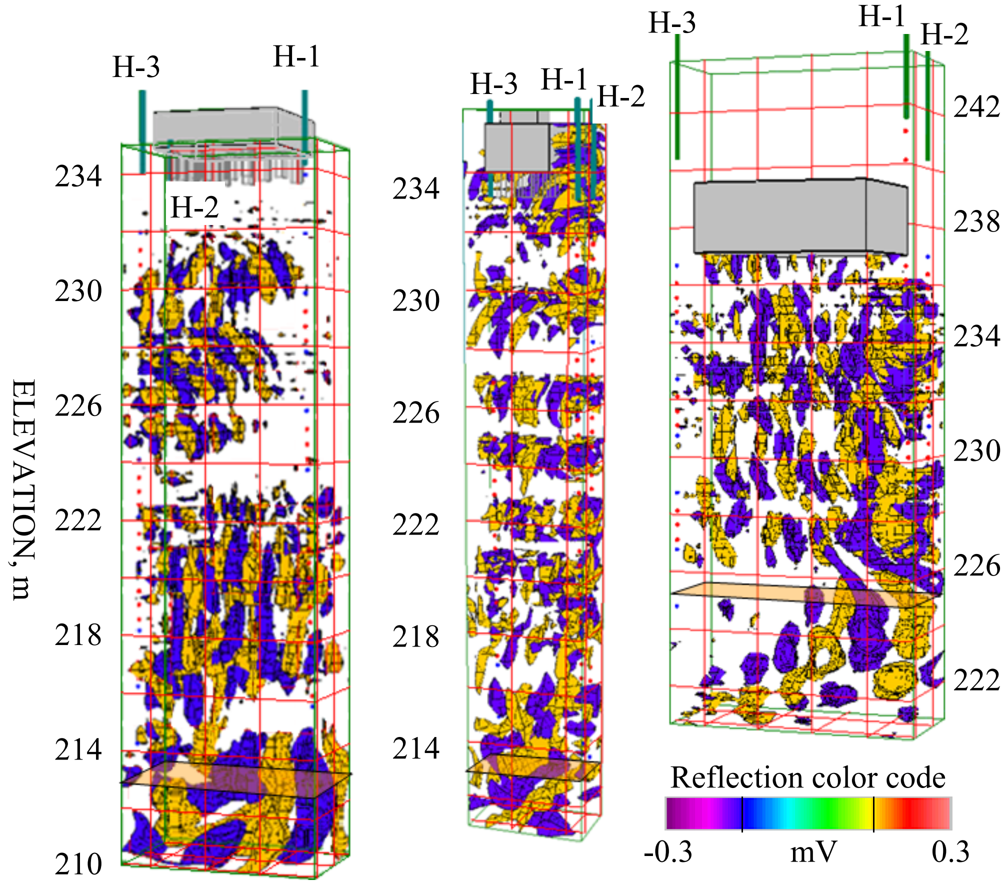

Figure 6. Pile-like anomalies in reflectograms for Abutment A (left), Middle Pedestal (center), and Abutment B (right). Orange planes marks depth of piles assessed based on seismic reflection data.

Horizontal sections through images shown in Figure 7 (looking down the piles), appear to show a tendency to form ring-like alignment of rounded anomalies centered with respect to individual holes rather than a regular patterns of individual piles. Also the anomalies appear to change their polarity intermittently with distance from each hole. This effect is particularly obvious for the Abutment B, in part due to a significant shift between the center of the surveyed pile foundation, and the center of gravity for the three survey boreholes.

In general, the results point out to new challenges that may be related to: (1) a pattern of piles and its density, (2) perturbations in the ground velocity and attenuation insufficiently represented by the velocity model, (3) a need for a denser coverage/shorter distances between hydrophones and for additional source locations at or above the pile caps, (4) a need for shorter waves, and (5) a need for the proper

compensation of phase shifts in the spectra of reflected waves that may be associated with the ratio between seismic wavelengths and the size of piles, and with changes of that ratio following local velocity changes in the ground.

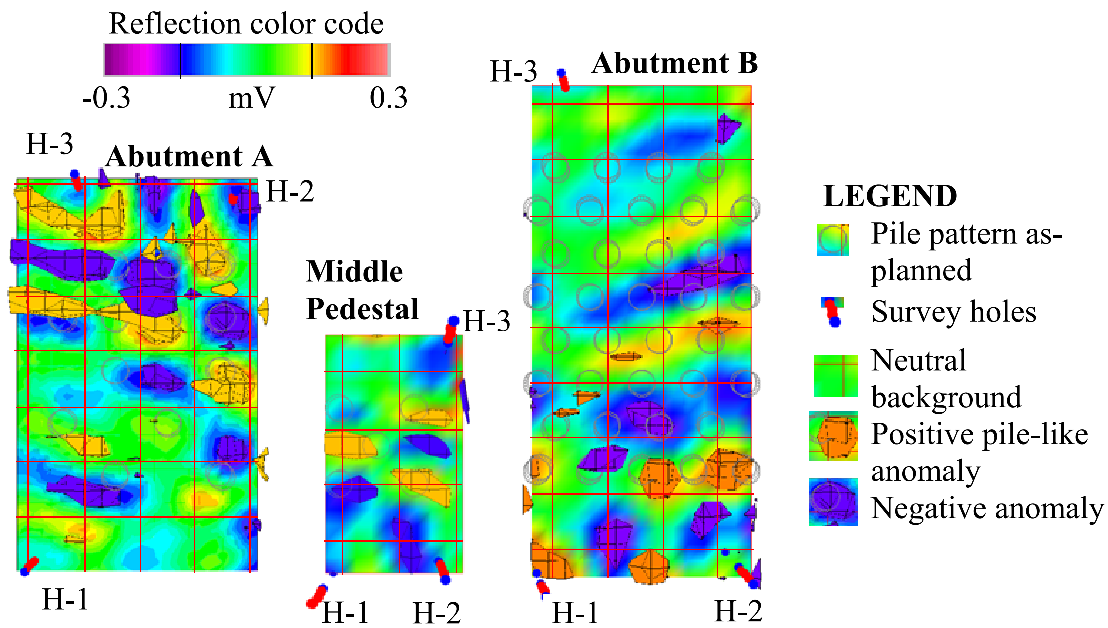

Figure 7. Plan view of contoured reflectors and reflectogram slices for Abutment A at elevation 216 m, Middle Pedestal at 214.5 m, and Abutment B at 227 m.

CONCLUSIONS

1. The seismic data confirmed that the concrete piles significantly increase the average velocity of seismic waves measured in parts of the ground which elastic parameters are lower than in concrete;
2. Comparing the velocity profiles measured in the neutral ground near the pile foundation, with the profile through the cluster of piles in that foundation allows assessing the minimum depth of the piles;
3. The 3D images generated by the velocity tomography:
    a. have a tendency to "fuse" the multi-pile structure into a larger monolithic feature;
    b. for piles located near the paths of recorded seismic waves, and crossing the boundary between different velocity grounds, these images appear to "identify" piles as spikes protruding toward lower velocity ground.
4. Detection of piles using either seismic tomography or reflected seismic waves is possible for piles or their sections that cross the ground which acoustic impedance differs from that of the piles;
5. The 3D velocity tomograms appear to provide an effective velocity model for processing reflected seismic waves to image individual piles;
6. The images generated using reflected waves (reflectograms) appear to demonstrate relatively uniform vertical characteristics of piles for Abutment B, the Middle Pedestal, and for the lower part of Abutment A. Perturbations in

the pile image for Abutment A are likely related to significant ground changes that may require finer vertical coverage for Single Hole Reflector Tracing to properly address those changes.

7. For three survey holes per site the pile imaging appears the most effective near the geometric center of the triangle formed by the holes.
8. Cross-sections though reflectograms indicate an intermittent pattern of positive and negative anomalies that appears tangential to the survey holes, while they also appear to match the pattern of the piles. The phenomenon is likely related to the improper wavelength of reflected waves.
9. Forward modeling needs to concentrate on effects of wavelength, pile patterns, configuration of source-hydrophone array, location of survey holes with respect to the target, phase shifts in spectra of reflected waves versus the diameter of piles, and adding source points at the pile caps, or at the ground surface above the caps.
10. The results of forward modeling have to be verified by the new field data.

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