LEVERAGING EXISTING INFRASTRUCTURE: USING WHAT'S ALREADY IN THE GROUND

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Abstract

Much of the highway infrastructure in the United States was built in the 1960's and 1970's and is currently being evaluated for upgrade and/or replacement. Original design drawings of the structure foundations are generally available; however, in many cases "as built" information was not archived. Confirming the condition of unknown bridge foundations may allow the use of existing infrastructure in upgrading these structures, saving significant amounts of time and money. By using multiple geophysical methods, NSA Geotechnical Services has been able to characterize existing, unknown foundations and provide critical information to engineers, allowing them to make a more informed decision on incorporating existing foundations in the new highway design.

This paper will review case studies where NSA Geotechnical Services has utilized cross-borehole seismic, cross-borehole GPR, and resistivity methods to characterize unknown bridge foundations. The applications and limitations of each geotechnical method will be discussed. Also, a brief discussion of new methodologies currently under development and being considered by NSA for characterizing unknown foundations will be included.

Introduction

Expanding capacity for roads and highways seems to be a never-ending task. Much of the highway infrastructure in the United States was built in the 1960's and 1970's. Although the designs and blueprints are available, whether structures were actually built to specifications is not always known. Understanding whether bridge piers were constructed as designed allows contractors to use existing infrastructure in expanding highway capacity, saving time and money on large construction projects.

The Pittsburgh area is in the midst of multiple construction projects with a goal to alleviate congestion on current roadways by expanding the carrying capacity of these existing roads. One possible "pinch point" in most road projects is the capacity of bridges. As old bridges are replaced or upgraded, it becomes critical to understand whether the existing foundation can be used in the new design. By using seismic tomography, corroborated by electrical resistivity and ground-penetrating radar (GPR), NSA Geotechnical Services is able to determine if existing bridge piers are, in fact, founded on competent rock, allowing them to be reused in the new highway design.

Background: Seismic Imaging

Seismic tomography is based on the principle that acoustic waves have different propagation velocities through different types of ground. That is, seismic waves travel faster in strong, competent material and slower in weaker materials (e.g., voids, broken or weathered rock, soil) (Nur (1); Shea-Albin, et al. (2); Yu (3)). Velocity tomographic images represent the ground velocity as measured between

seismic sources and receivers. The accuracy and resolution of a tomographic image is a function of the source and receiver geometry.

To determine the seismic velocities of a survey area, the time required for seismic energy to travel from known source and receiver locations is measured. The velocity is then computed by dividing the distance traveled from source to receiver by this travel time. In ground with a homogenous velocity distribution, this distance is simply a straight-line distance, or straight ray path, from the source to the receiver. However, in ground with velocity variations, this distance may significantly increase due to curvature of the ray path through higher velocity ground between the source and receiver. With appropriate source and receiver geometry, it is possible to iteratively construct an accurate velocity model of the ground surveyed. Distortions in the velocity model may appear in varying degrees as a consequence of the ground characteristics and the source and receiver geometry. Figure 1 demonstrates this distortion for a marginal, two-dimensional, source and receiver geometry.

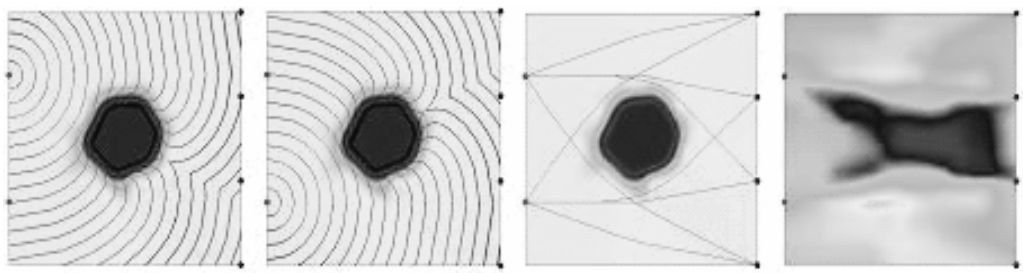

Figure 1. Example of tomographic reconstruction.

There are numerous factors that may cause variations in velocity. Different ground types usually have different material/seismic properties, but variations within the same ground type are also commonly encountered. Variations in stress, fracture extent, water saturation, soil compaction, etc., all may have a significant effect on velocity. In areas where geological features such as fracture zones, faults, subsidence zones, or cavities exist, the seismic waves may travel at a lower velocity, or may travel across an increased distance to pass around the anomaly and suffer increased attenuation. The same type of behavior may be noted in rocks of varying lithology as harder, more competent materials propagate seismic waves at higher velocity and lower attenuation than softer, less competent or less consolidated rocks.

Seismic tomography, in its current state, is best employed as a tool for detailed investigations. Other methods such as ground-penetrating radar (GPR) and electrical resistivity (ER) are methods for doing reconnaissance.

Etna Interchange

AWK Consulting Engineers, Inc. approached NSA Geotechnical Services (NSA) to conduct a geophysical investigation to ascertain whether the existing bridge foundations at the Etna interchange were founded on competent rock. The specific objective of the survey was to determine the depth of the piles and render an opinion about whether or not the existing piles are point-bearing on rock or friction piles. NSA proposed using its seismic velocity cross-borehole tomography system, RockVision3D™, as the primary investigative technique. To corroborate the tomography survey results, NSA conducted a resistivity survey for one of the piles at each survey location. NSA also conducted a cross-borehole, GPR survey as an additional corroborating investigation method.

Procedure

The location to be surveyed was Wall U-Ramp U of the US Route 28 Etna Interchange. Three cased boreholes were provided for the pier locations. These three holes were configured so that two of the panels between boreholes cross through the pile cluster (Figure 2). The third panel crossed through ground that does not include piles to provide control for the survey. Calculating the location of instruments within the boreholes was critical to ensure the accuracy of the source and receiver locations

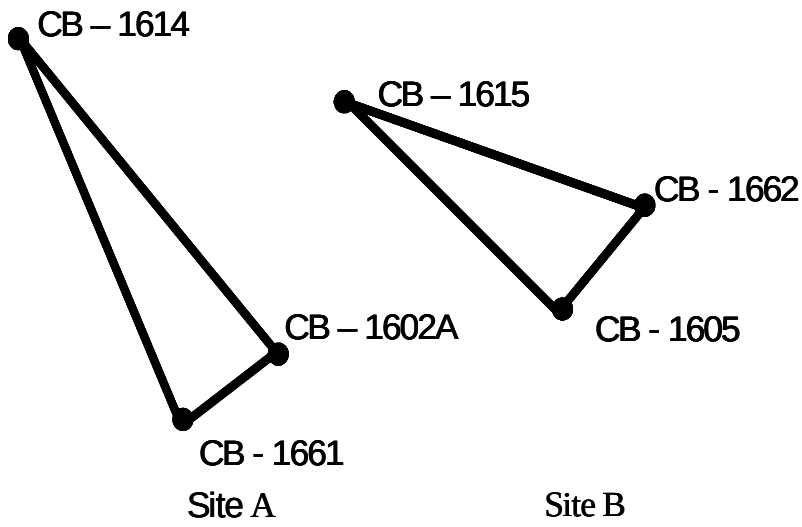

Figure 2. Borehole layout for sites A and B.

during the survey; therefore, a verticality survey was conducted for each borehole. Both the seismic and GPR survey used the same boreholes.

Seismic Cross-hole Tomography Survey

NSA's seismic velocity cross-borehole tomography, RockVision3D™, was used to collect field data and generate two-dimensional and three-dimensional tomographic images of the ground defined by the boreholes around each pier. RockVision3D™ is a seismic tomography system that provides two-dimensional and three-dimensional velocity images of the ground between boreholes and/or boreholes and the surface. RockVision3D™ provides information on ground conditions or anomalies with differential seismic velocities or attenuation characteristics.

NSA conducted this cross-hole velocity tomography survey by pairing a seismic source and a string of receivers in adjacent boreholes to propagate and capture seismic signals transmitted between source and receiver boreholes. Each source-receiver array did result in data that formed a vertical panel containing information on the velocity structure between the boreholes. The collected seismic data were analyzed, filtered, and processed creating a series of two-dimensional tomograms and three-dimensional contour velocity images and section views of the ground between borehole pairs. For this survey, a hydrophone string with 18 hydrophones served as down-borehole receivers; the hydrophones were spaced at 3.28-ft (1-m) intervals, resulting in each string having receivers along 56 ft (17 m) of its length. An Etrema magnetostrictive, swept-frequency source was used to generate seismic energy in boreholes adjacent to the hydrophones. Each seismic signal initiation triggered the recording of seismic waves by the seismograph. Where steel or Raymond/monotube concrete piles exist within the surveyed area, they would be indicated in the tomograms as relatively higher seismic velocity zones than the surrounding ground.

Resistivity Survey

To conduct the resistivity survey, an electrical node was connected to a conductor previously connected to one of the piles at each of the survey sites. A second electrical node was attached to a grounding electrode in line with and beyond one of the boreholes used for the seismic and GPR surveys; this borehole was perforated to measure conductivity using the groundwater. A borehole probe, with terminals spaced 1 ft (0.305 m) apart, measures this potential difference. Because the probe can only measure resistivity in water, the resistivity data start in each drill hole at the top of the water table. The potential difference measurements were taken at 3.28-ft (1-m) intervals from the top of the water table to the bottom of each borehole. The potential difference in the electrical field would be minimal from the water table to the bottom of the steel piles, and variations in resistivity are a consequence of differential ground conductivity. At the bottom of the steel piles, the electrical field created by the energized pile and the remote node would decrease, and the potential difference measured by the probes in the borehole would increase significantly. Immediately below the depth of the steel portions of the piles, the electrical field would approach zero, and the potential difference measured by the borehole probe would return to zero.

Ground Penetrating Radar Survey

NSA also conducted a cross-hole GPR survey to corroborate the seismic and resistivity surveys. The same procedures were followed as in the seismic survey except a radar transmitter was used as a down-hole source which transmitted a signal to a radar receiver positioned in adjacent boreholes. It should be noted that one major difference between the seismic and GPR data collection methodologies is that the GPR transmitter and receiver were always positioned at the same elevation in the source and receiver holes, whereas for the seismic survey, many different elevations were used. Where there are steel or Raymond/monotube piles in the ground between any of the boreholes, the velocity and the magnitude of the radar signals would be affected. The average velocities of the signals passing through piles would be lower as the radar signal velocity of the piles would be less than the surrounding ground. Attenuation of the radar signal would be greater for signals passing through piles as a significant portion of the signal would be reflected and dispersed by the piles.

Data Analysis and Interpretation

Seismic Cross-Hole Tomography

The data quality for both sites A and B was acceptable. The images indicated the measured seismic velocity of a volume of ground defined by the boreholes. For site A (Figure 3), the individual piles appeared to be detectable as relatively higher seismic velocity anomalies within the fill and soil material above the bedrock to a depth of approximately 690 ft (210 m).

For site B (Figure 4), only the pile cluster was indicated above the bedrock as a zone of relatively higher velocity ground, extending to approximately 680 ft (207 m). For both sites A and B, there was also a very clear indication of low-velocity anomaly pockets in the top of the bedrock where the piles were driven into the bedrock.

The seismic tomography surveys for both site A and site B indicated that the piles were point-bearing on rock, and, in fact, the piles were driven into the bedrock surface when installed.

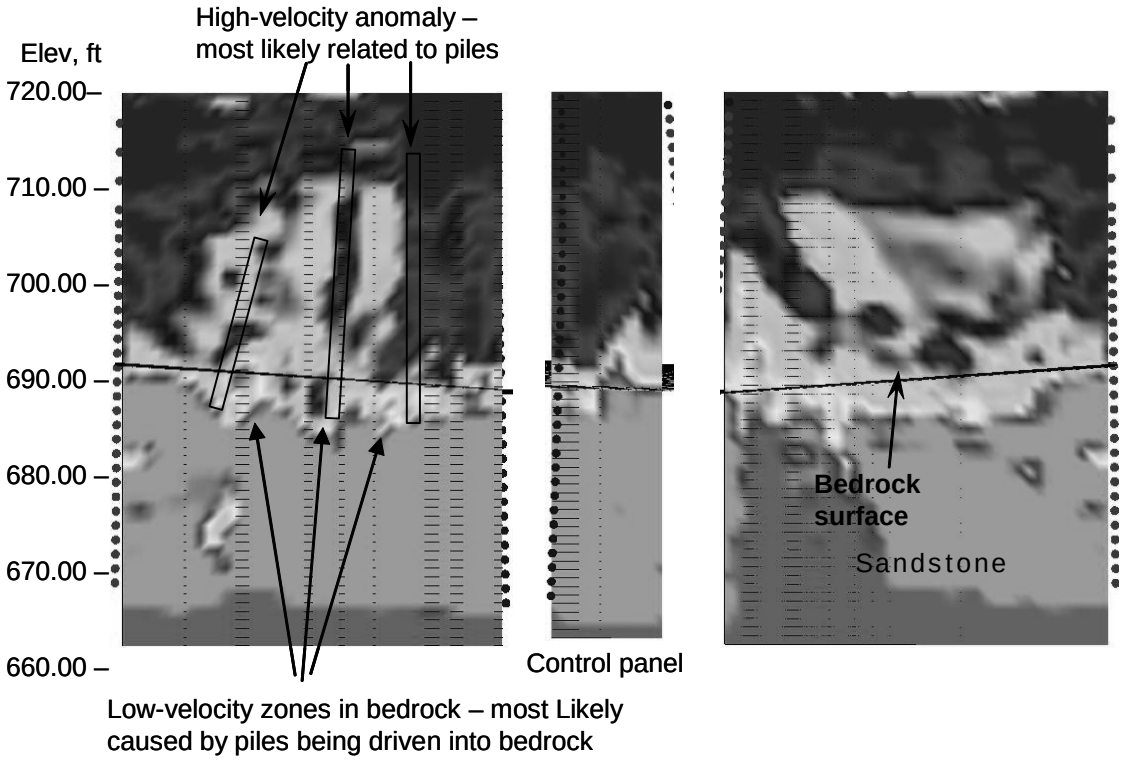

Figure 3. Ramp U Site A. Side view of vertical tomograms between survey boreholes.

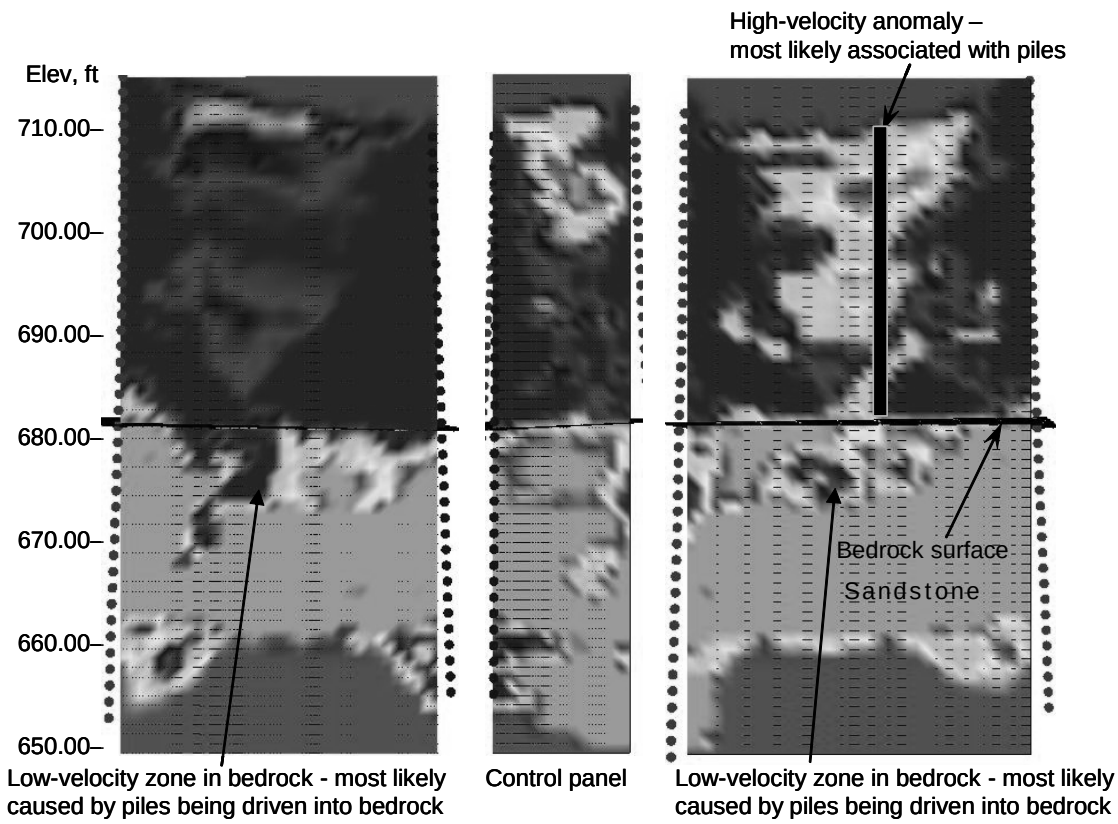

Figure 4. Ramp U, Site B – Side view of vertical tomograms between survey boreholes.

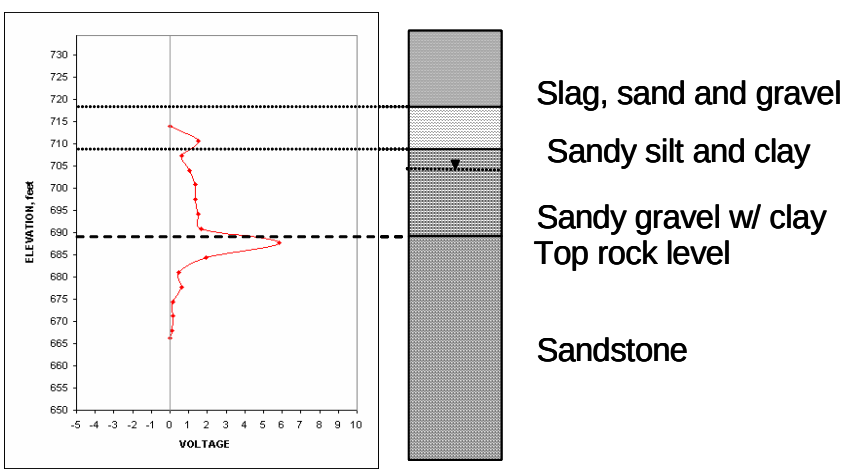

Figure 5. Ramp U, Site A–Resistivity survey profile and associated geology.

Resistivity

The data quality for both sites was acceptable. These figures showed the depth in the borehole from the surface versus potential difference in the electrical field created by the energized piles and the remote node. The graph for site A (Figure 5) clearly indicated that there was a continuous electrical conductor (the pile) from the node connected to the top of the piles to an elevation of approximately 689 ft (210 m). As a consequence of the probe borehole being several feet away from the pile and the triangular shape of the electric field created by the energized pile and remote surface probe, it was concluded that the steel portion of the pile is slightly deeper than this elevation. The drill-hole information indicated the top of sandstone bedrock at 688.9 ft (210 m) elevation.

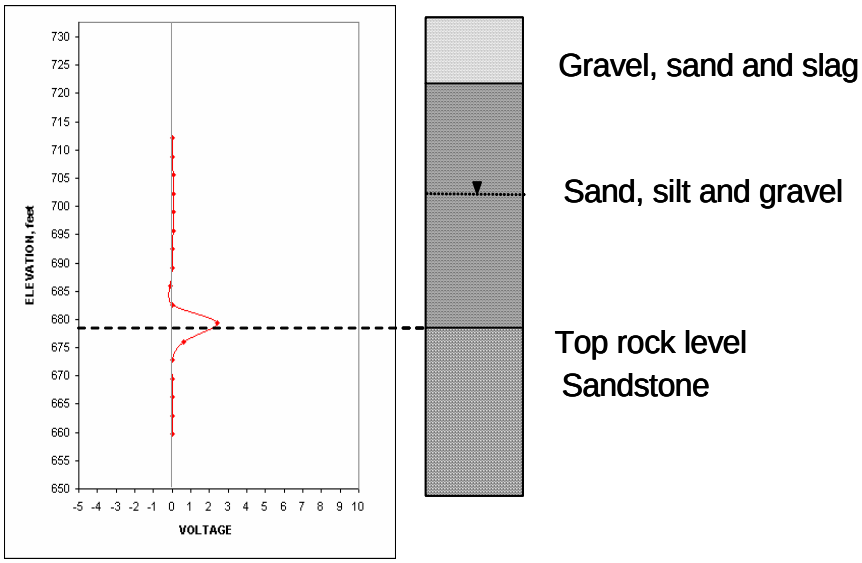

Figure 6. Ramp U,Site B–Resistivity survey profile and associated geology.

The graph for site B (Figure 6) clearly indicated that there was a continuous electrical conductor (the pile) from the node connected to the top of the piles to an elevation of approximately 679 ft (207 m). The drill-hole information indicated the top of sandstone bedrock at 678.3 ft (206.9 m) elevation. Again, because of the geometry of the electrical field and the probe, the metal portion of the pile most likely extended slightly deeper than 679 ft elevation (207 m). The resistivity surveys for sites A and B indicated that the piles were point-bearing on rock.

GPR Survey

The data for site B were acceptable and provided clear indications of the pile cluster tip elevations. The data for site A were poor, most likely due to high radar conductivity of the ground around this site. As a consequence, the GPR survey for site A was inconclusive.

For site B, the first image (Figure 7) showed the control panel between drill holes CB-1605 and CB-1662; the second image showed the panel through the pile cluster between drill holes CB-1615 and CB-1662; the third image showed the panel through the pile cluster between drill holes CB-1615 and CB-1605. The control panel showed the GPR signal passing through the ground above the top of the sandstone bedrock. At an elevation of approximately 678 ft (206.8 m), which corresponds to the top of

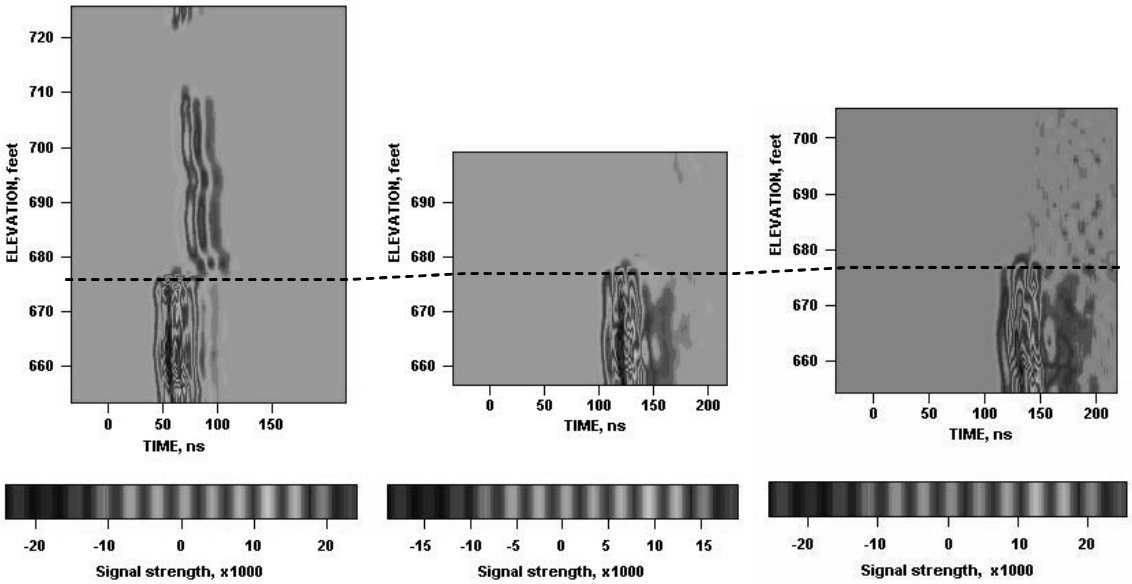

Figure 7. Ramp U, Site B – Radar panels.

bedrock, the signal became stronger and had a higher velocity.

The second and third panels, through the pile clusters, indicated a total attenuation of the GPR signal above 678 ft (206.8 m) elevation. This was expected and was most likely a consequence of the GPR signals being reflected and attenuated by the steel piles. Once the GPR transmitter and receiver were below the elevation of the piles, the signal was detectable.

The GPR survey for site B indicated that the piles are point-bearing on rock.

Summary Results

The seismic and resistivity surveys conducted for site A ***strongly indicate that the piles were point-bearing on bedrock,*** and there were no indications in either of these surveys that the pile tips do not extend to bedrock. The GPR survey for this site was inconclusive and provided no information on the pile tip locations. The seismic, resistivity, and GPR surveys conducted for site B ***strongly indicate that the piles were point-bearing on bedrock,*** and there were no indications in any of the surveys that the pile tips do not extend to bedrock.

Economics

The cost for the geophysical investigation conducted by NSA was on the order of $25,000. In the absence of a definitive analysis regarding the condition of these bridge foundations, the only option would have been to assume none of the existing infrastructure could be used and an entirely new bridge foundation system designed and installed. That would raise the costs on this project by $2.5M or 100 times the cost of geophysical investigation.

Had the piles been friction piles, piles not driven to bedrock, they still could have been incorporated into the new design for this interchange. However, the new design would have been engineered differently for friction piles. In general, there is great benefit in knowing the ground conditions around an existing bridge foundation in the redesign of a highway interchange.

New Methodologies

In August of 2001, NSA was awarded an Advanced Technology Program grant from the National Institute of Standards and Technology for a program that combines three-dimensional ground imaging with numerical modeling. This project will integrate seismic tomography and holography with state-of-the-art numerical modeling technologies. Holographic/tomographic seismic imaging will be used to develop “seismically calibrated” models - engineering computational models based on the actual anisotropic, non-homogeneous constituents of the in situ three-dimensional rock and soil mass.

In addition to using the results of seismic investigation to create these “seismically calibrated” models, NSA is making advances in two areas related to seismic imaging. The state-of-the-art for current seismic investigations depends on picking first arrivals of seismic energy and using those data to compute seismic velocities. NSA’s new analysis methods will use the full waveform of seismic energy received, improving the accuracy and detail of seismic models.

NSA is also developing computational modeling technology that will process data from surface-mounted sensors. By relying more on surface-mounted instrumentation, the costs for performing seismic investigations will decrease because the cost of drilling boreholes is eliminated. NSA is also developing self-locating, wireless sensors as part of this effort. Self-locating sensors will eliminate the need for all sensor locations to be surveyed. By using wireless communication technology for these devices, the effort of positioning and removing the wires currently required to transmit data from seismic sensors to a seismograph is eliminated. These innovations will result in reduced costs and effort related to performing the data collection portion of seismic investigations.

Conclusions

The images of the bridge piers produced by RockVision3D™, coupled with data from the GPR survey and resistivity testing, show definitively that the existing structures are founded on competent rock. Rather than having to specify totally new structures to support the new bridge, accurate information about the current structures allow them to be incorporated into the new design. This greatly reduces the cost

and schedule for the completed project. Having better information enables better decision-making. By removing the guesswork, projects can be executed safely and economically in a timely manner.

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