Conventional Processing Techniques and Nonlinear Refraction Traveltime Tomography for Imaging Bedrock at an Eastern Massachusetts Coastal Site

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ABSTRACT

A seismic refraction survey was conducted at a coastal site in eastern Massachusetts to determine bedrock depth and locate areas where overburden thickness is sufficient for the construction of a replacement storm-drainage system. Since the site is in a tidal zone, the saturated thickness of the overburden is constantly changing. Additionally, the depth to bedrock varies from a few feet to 50 or 60 feet.

We use a nonlinear refraction traveltime tomography technique (Zhang et. al., 1996) to evaluate this complex tidal environment and compare the modeled results with those acquired using more conventional processing techniques such as the crossover-distance and iterative ray tracing methods. We find good correlation of the methods along those lines closest to shore and least influenced by tidal changes and organic deposits. However, conventional methods fall short where organics and changing saturation conditions cause abrupt changes in lateral and vertical velocities.

INTRODUCTION

As part of a sewer upgrade project in the Boston area, a new storm-drainage system is being constructed to service several eastern Massachusetts coastal communities. To reduce project costs, the new service will need to be constructed where bedrock is relatively deep, so that costly blasting is not required. A seismic refraction survey was conducted to determine bedrock topography and locate those areas where overburden is thickest. Because of complex geologic conditions in the Boston Basin, depth to bedrock is quite variable. We chose to evaluate data using two conventional techniques, Crossover Distance and SIPT2 (an iterative ray-tracing method that uses the delayed time method as an initial model), and compare the results with those obtained using a nonlinear refraction traveltime technique developed and described by Zhang et. al., (1996).

DATA ACQUISITION

Approximately 1,300 feet of seismic refraction data were collected along two traverses parallel to, and three traverses perpendicular to, the west shore of the Weymouth Fore River in Braintree, Massachusetts. Data were collected using an OYO DAS-1 seismograph with a 24-channel geophone array. A sampling rate of 0.25 ms was chosen. Borings from nearby locations indicated that bedrock could be as deep as 50 to 60 feet, but as shallow as 5 to 10 feet. Geophone spacings of 10 feet were used along lines parallel to the shore, while 5-foot spacings were employed along perpendicular lines where tidal changes limited the size of the array.

Single-element 40 Hz geophones were used during this survey to minimize interference from low-frequency ambient vibration sources (notably wind and waves). To preserve the wetland grasses, use of an explosive

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that creates an air wave when impacted with a hammer. When the hammer was used, the number of stacks per shot point was variable, ranging between 4 and 10, and the quality of the stacked seismic signal for each shot point was verified in the field. When used, the nozzle of the seisgun was buried 1.5 to 2 feet below ground surface. A minimum of 7 shot points were made for each 24-geophone spread -- 2 end shots, 2 offsets, and at least 3 intermediate shots. Generally, for the purpose of nonlinear tomographic imaging, intermediate shots were obtained at 20-foot intervals using the hammer as a source. End shots and offset shots were obtained using the seisgun.

DATA ANALYSIS

The OYO seismograph recorded all refraction data to an internal hard drive and floppy diskette, and transferred them to a desktop computer and Sun workstation. Seismic data analysis was accomplished using three different methods: the crossover-distance method (Dobrin,1976), the SIPT2© iterative ray tracing technique (Scott, 1973), and nonlinear traveltime refraction tomography (Zhang, 1996). The first two techniques are used conventionally by industry to process seismic refraction data. The nonlinear traveltime tomography method uses a raytracing program that can precisely calculate traveltimes and raypaths, and employs a nonlinear optimization method to update model parameters and raypaths to fit recorded data. Requiring the computer-power of a workstation, nonlinear traveltime tomography makes many computationally-intensive iterations to fit model parameters to actual velocity structures.

The SIPT2 Iterative Ray Tracing Technique

The SIPT2 iterative ray tracing technique, first introduced by Scott (1973) requires a laptop or desk top computer. First, data are input into the computer and velocities assigned for each refractor layer based on actual data. An initial model is then created based on the delayed time method. Next, the program calculates the shot-geophone first arrival times for each raypath in the model and then estimates the misfit between predicted and real data. The misfit may be large (i.e. calculated arrival times different from real data) if the initial model is too simplistic and refractors have irregular topography. The program looks at the delay times of the calculated model and adjusts the model accordingly. The computer iteratively compares calculated model arrival times along each ray trace from shot to geophone with actual arrival times and adjusts the model after each iteration. After three iterations a reasonable fit between calculated and real data is found (i.e. the misfit between real travel times along assumed raypaths is minimized) and the refractor depth beneath each shot and geophone is then determined. The accuracy of the SIPT2 iterative method is contingent upon a reasonable initial model and the simplicity of the geologic structure. The program assumes that each velocity layer encountered is horizontally continuous, and that there are no lateral or vertical changes in velocity within any one layer.

Nonlinear Refraction Traveltime Tomography

A nonlinear refraction traveltime tomography method can reconstruct seismic velocity distribution from an arbitrary initial model (Zhang et al., 1996). The method makes no assumptions based on velocity or structure, and an input model may be as simplistic as a homogeneous half-space. Instead, the method relies on many computationally intensive iterations on a workstation to minimize data misfit. It includes a graphical method that can accurately calculate traveltimes and raypaths in any random medium and a nonlinear inversion approach that updates model and raypaths iteratively.

This method does not assume layered velocity structures or assume fixed raypaths. It uses a grid-based model with a large number of velocity cells. A regularization of Tikhonov method (Tikhonov and Arsenin, 1977) is applied to correlate data variance with model variance. This effectively removes non-uniqueness of inversion solutions but produces one solution that has high certainty. The method utilizes two types of data from a seismic refraction survey: the traveltimes between shots and receivers, and the gradients of the traveltime curves. The tomographic imaging procedure constructs a velocity model based on fitting these two types of data and based on the model covariance.

RESULTS

First arrivals were picked from the seismographs using SIPIN (on the PC) and ProMAX (on the Dec workstation). Most seismograms showed high signal-to-noise ratios, enabling confident first-arrival time picks.

Figure 1 shows SIPT2-generated results from data obtained along SL-1, which is located closest to shore. Figure 1 shows the thickness and approximate velocity for each identifiable layer; interpretation of the material type have also been made, based on the weighted averaged velocities calculated by SIPT2 and verified using the Crossover Distance method. Materials with two distinct velocity ranges were interpreted along SL-1. The uppermost material, with a velocity range of 4,400 to 5,000 feet per second (ft/s), is interpreted as partially to completely saturated silt and clay. The deeper material, with a velocity ranging from 13,500 to 15,000 ft/s corresponds to bedrock. Bedrock appears to be shallow-- approximately 4 feet below grade to the north by Station 7+50 and about 10 feet between Stations 4+50 through 5+00.

Nonlinear refraction traveltime tomography produced a similar model to that of the SIPT2-generated model. Nonlinear refraction traveltime tomography results indicate a relatively simplistic velocity structure: a thin low velocity zone (about 2 feet at Station 7+50) overlying a high-velocity zone and a high-velocity contrast between the two zones.

Two borings along SL-1, located about 8 feet west of Station 6+90 and 2 feet west of Station 4+60, confirm that bedrock is shallow. Bedrock was located at 2 feet below grade at boring I-6 (near 6+90) and at 10 feet at boring I-6A.

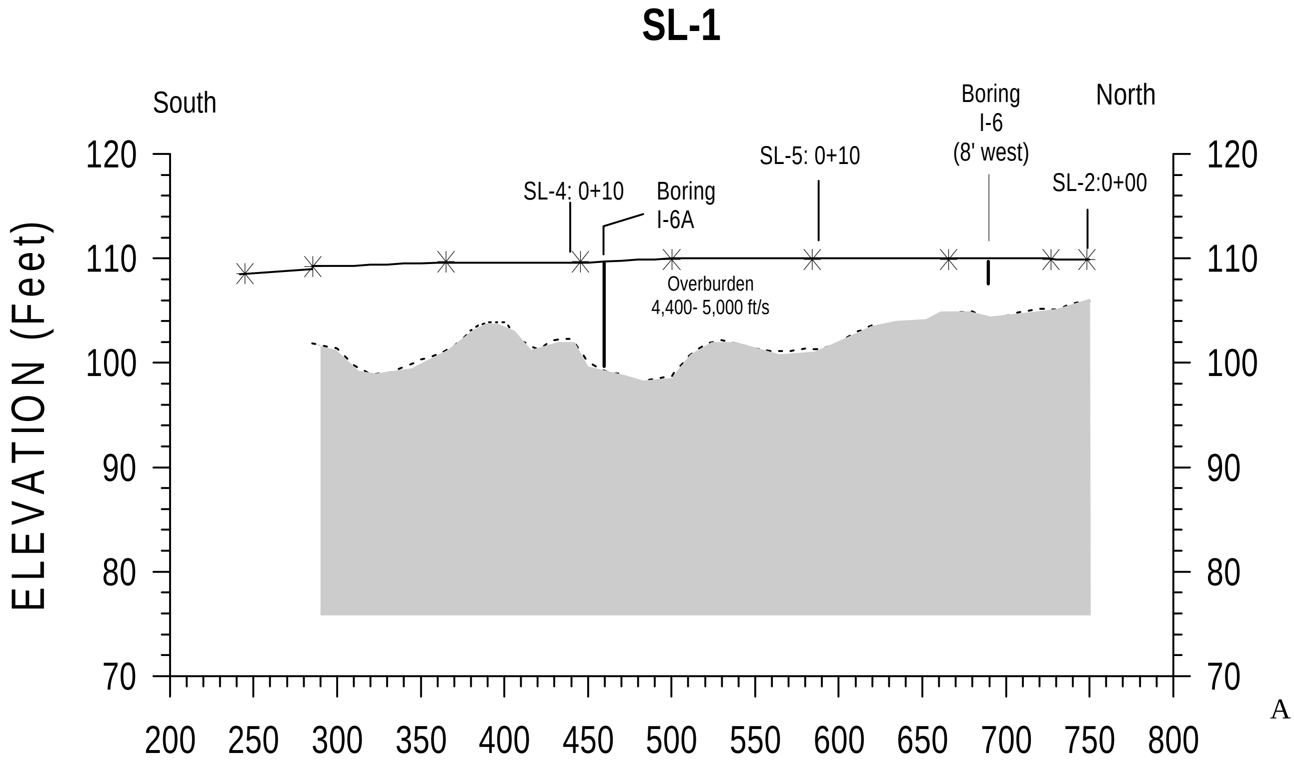

Figure 1: Modeled SIPT2 results for SL-1. Interpreted bedrock refractor ranges from 4 to 10 feet below grade. Interpreted depths were cross-referenced using the Crossover-Distance method.

more complex velocity structure was encountered along SL-3, located within the tidal zone and further from shore than SL-1. When traveltimes are plotted as a function of distance, the gradients of traveltime curves progressively change, and indicate that the overburden velocity generally increases with depth. We attribute this phenomenon to the continually changing saturation conditions caused by tidal fluctuations. Also, a low-velocity zone was observed between Stations 5+20 through 7+00, which is attributed, at least in part, to organics.

Figure 2 shows SL-3 as modeled using SIPT2 and correlated with the Crossover-Distance method. Note that the model may not be reliable as the discontinuous velocity layer from Stations 5+20 through 7+00 and changing vertical velocity within the overburden violate the assumptions made by the SIPT2 program. The model shown in Figure 2 was created from a three-step process. First, as a crude estimate, a two-layer model was assumed, with a 5,000 ft/s overburden velocity assigned. Because SIPT2 does not allow to adjust for lateral changes in velocity, the model assumes that discrepancies between the initial model and actual traveltimes are caused by bedrock topography, and adjusts the bedrock refractor accordingly. Next, an additional layer was assigned with a weighted average velocity of 2,800 ft/s. (Actual velocities ranged from 1,800 ft/s to 3,500 ft/s.) Because SIPT2 was not designed to model discontinuous layers, we assigned the closest geophone to each shot to this low-velocity “layer” thereby attempting to make it appear thin and continuous. This helped establish an approximate model for the bedrock refractor beneath the low-velocity layer; we used the two-layer SIPT2 model to establish the depth to bedrock everywhere else. The final step was correlating SIPT2-modeled results with the Crossover-Distance method and adjusting the model accordingly.

Figure 3 shows the complex velocity structure generated using nonlinear traveltime refraction tomography. Velocities higher than 13,500 ft/s are attributed to competent bedrock, while those ranging from 7,500 ft/s to 11,000 ft/s are most likely attributed to fractured and weathered bedrock. (Given the geologic history of the Boston Basin, a thin till layer, with typical velocities of 6,000 ft/s to 7,500 ft/s could also be present overlying bedrock. No evidence of till was found in nearby soil borings, however.) Velocities ranging from 3,500 ft/s to 5,400 ft/s are attributed to overburden.

Refractor boundaries shown in Figure 3 are not as clearly defined as in the SIPT2 model. However, because the velocity-generated model was produced without the assumptions limiting the SIPT2 model, it is believed to be more accurate. Nonlinear refraction traveltime tomography clearly defines the low-velocity zone in the middle of SL-3. The model also shows a high-velocity zone from Stations 3+20 through 4+00. The results of the nonlinear refraction traveltime tomography indicate that velocities range from 7,000 ft/s to 10,000 ft/s. Visual inspection of this area suggests that this localized high-velocity zone may be caused by shallow, highly weathered bedrock.

CONCLUSION

Conventional seismic refraction travel time inversion techniques, such as the one employed by SIPT2, assume constant velocity within any one layer and assume that the boundaries of layers are continuous. If these conditions are met, the SIPT2-generated model produces an accurate, high-resolution representation of layered refractors. The uncertainty of refractors can be high and the model can produce non-unique solutions if the velocity structure is complex.

The nonlinear refraction traveltime tomography method creates a high-resolution, high-certainty velocity model that is independent of layered assumptions. In a simplistic velocity model, the resolution of refractors is more accurately defined by SIPT2. However, because nonlinear refraction traveltime tomography can compensate for incremental velocity changes in both lateral and vertical directions, it creates a more realistic model of a complex tidal environment.

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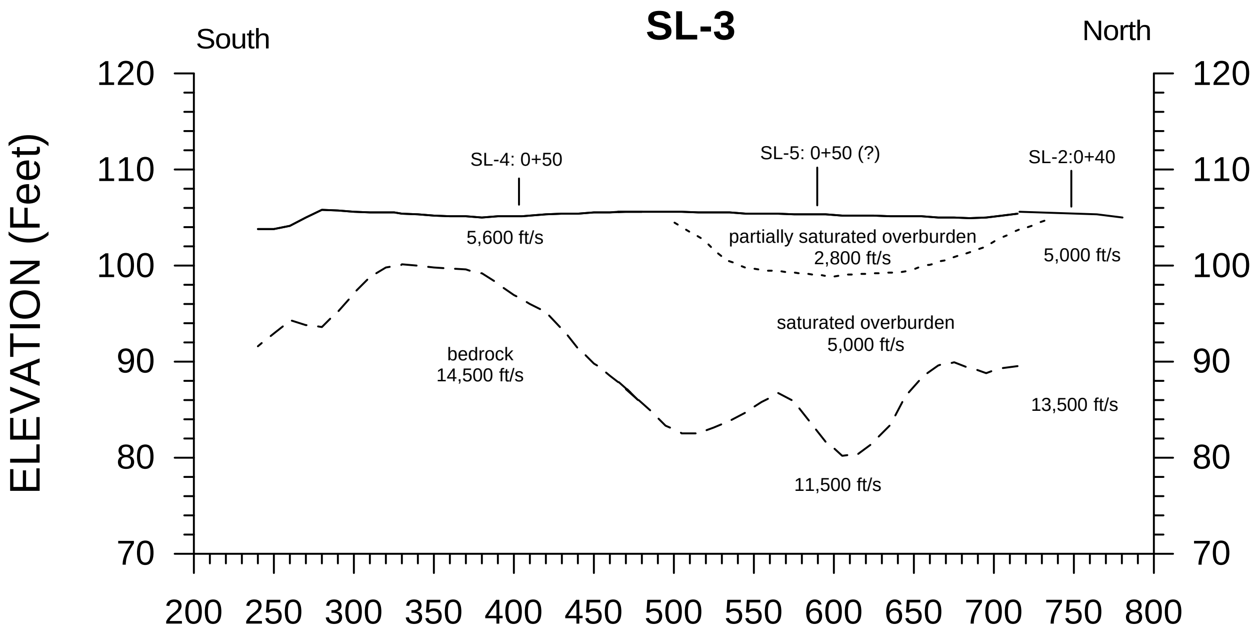

Figure 2: SIPT2-generated model along SL-3. Because of a discontinuous low velocity zone between Stations 5+20 to 7+00, modelled results depicting bedrock topography may not be accurate. Depth calculations using the Crossover-Distance method have been incorporated into the SIPT2 model to give a more accurate representation of the bedrock topography.

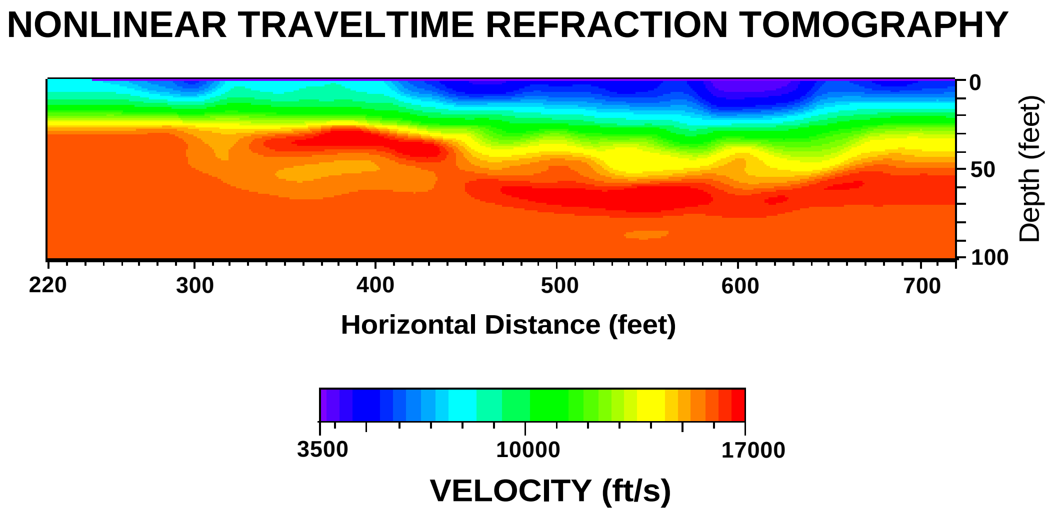

Figure 3: Velocity model generated using the nonlinear traveltime refraction tomography method. Note that refractor boundaries are not as sharply defined as in the SIPT2-generated model above, although the complex velocity structure along SL-3 is more accurately represented.

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