Mapping Soft Soil Zones and Top-Of-Bedrock Beneath High-Traffic Areas In Honolulu Using 2D ReMi

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ABSTRACT

Two-dimensional seismic refraction microtremor data were acquired, processed and interpreted for the Honolulu High-Capacity Transit Corridor Project – west of Honolulu, Oahu, Hawaii. The objective was to image the lateral and vertical extent of *soft-soil* conditions and determine the *depth-to-bedrock*. Approximately 4.28-line km (2.66 miles) of two-dimensional (2D) refraction microtremor (ReMi) data was acquired along 12 lines. Data were acquired along the Farrington and the Kamehameha Highways. Line locations were selected to obtain additional subsurface information between and below geotechnical borings. Results indicate that thick soft-soil conditions exist; and, that the basalt bedrock has considerable relief. The bedrock can be encountered as shallow as 1.5 m (5 ft), to as deep as 70 m (230 ft) in this area beneath the existing highways. An innovative application of 2D seismic testing successfully mapped the lateral and vertical variability of the soft-soils beneath areas with very high traffic volume, without interrupting vehicle flow.

INTRODUCTION

In August 2008, Zonge Geosciences, Inc. (Zonge) conducted an innovative seismic survey west of Honolulu, Hawaii. Figure 1 outlines the project area, which generally lies between Waipahu and Aiea. Objectives of the seismic investigation were two-fold: 1) Determine the thickness and lateral variability of soft-soil deposits; and, 2) Determine the depth-to-bedrock.

To meet the objectives a 2D ReMi survey was performed. The surveys were conducted in areas of very high traffic volume along segments of the Farrington and [King] Kamehameha highways. The project follows the proposed alignment for the Honolulu High-Capacity Transit Corridor Project (HHTCP). The seismic data were acquired in (coned-off) traffic lanes, medians, and along sidewalks. Line locations were selected depending on crew safety, day of the week, and lane closure/accessibility. Geologic and geotechnical data were provided, in the form of boring logs and shear-wave velocity data, to aid the seismic interpretation.

In general terms, the geologic setting does not vary considerably over the 8.05 km (5-mile) survey area; that is, there are overburden soils overlying bedrock. However, for engineering design purposes the stiffness of the overburden and the depth to the bedrock are critical parameters. These design data are most commonly obtained with geotechnical drill holes, sampling and lab testing. Beneath most of the Honolulu area, the overburden materials are described as a complex series of soils that range from coarse-grained, loose- to very-dense sands and gravels (with cobbles) to fine-grained, very soft to very stiff clays. In addition to these coarse- and fine-grained soils, interbedded layers of coralline, mudflow or clinker deposits are also present within the overburden. Across this project area bedrock is defined as basalt. Outcrops and boring logs indicate that the bedrock has significant variability in the degree of weathering, fracture density, and other lithologic characteristics (i.e., vuggy, pillows, etc.). Depth to bedrock was anticipated to vary significantly beneath this portion of the HHTCP project site, with no consistent or regional dip. Similarly, the stiffness of the (undifferentiated) overburden was expected to vary considerably.

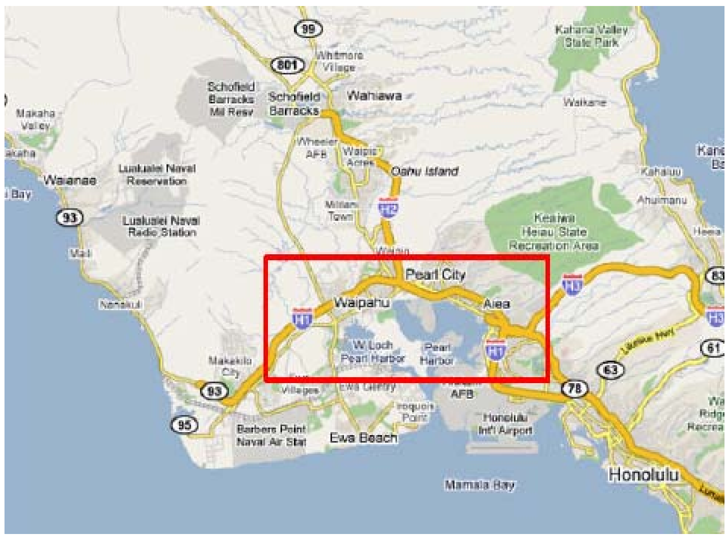

Figure 1: **Project location map showing the area of investigation (*red box*).**

Topographic relief on the bedrock surface is generally attributed to erosional features such as paleo-channels or relief caused at the time the basalt flow was deposited. As a result, the subsurface soil/bedrock interface is complex. The water table is typically shallow due to the proximity to the coast. Numerous borehole logs identifying soil classification, bedrock lithology, and associated geotechnical properties of the subsurface materials encountered were made available for correlation with the seismic data.

Scope and Method

The primary focus of the seismic survey was to define the thickness and lateral variability of the overburden soil deposits; and, to a lesser extent the soil / bedrock interface. The combination of a need for subsurface imaging, the complex geologic setting, and the field conditions of an urban, noisy, heavy traffic project area created a unique opportunity to apply a relatively new seismic method. The ReMi method was selected because it is not affected by saturated soil conditions, since it produces shear-wave velocity profiles.

The ReMi field method was selected because it satisfies all the conditions and survey needs described above. ReMi is relatively new, but it is becoming a standard and robust geophysical method for use in urban settings to derive the IBC site classification (Louis, 2001). ReMi is a one-dimensional (1D) '*seismic sounding*' technique that measures passive-surface wave dispersion to model the shear-wave (S-wave) velocity distribution with depth. The S-wave velocity sounding is obtained below a surface array of standard refraction-type geophones and recording equipment. The 2D approach has been utilized to image the soil / bedrock interface beneath rivers and in urban settings where noisy site conditions prohibit use of refraction, reflection, or active surface-wave (MASW) seismic techniques.

Line lengths were adjusted *on-the-fly* based on access, as dictated by local traffic control, as well as based the need for access to commercial businesses. Twelve locations were selected for seismic testing; however the actual line position was not finalized until the field conditions were assessed daily. Approximately 5.121 line km (16,800 feet) of data were acquired.

Independent line maps were generated using Google Earth images which are reasonably accurate; an example is shown on Figure 2. They indicate the general line location and nearby intersections and the geotechnical boring locations. Note that some of the line segments represent a continuous profile. For example, Lines 2, 3, 4 and 5 combine for over 1.68 line km (5,500 feet) of continuous 2D profile. An average of approximately 457 to 487 line m (1,500 to 1,600 feet) was acquired daily.

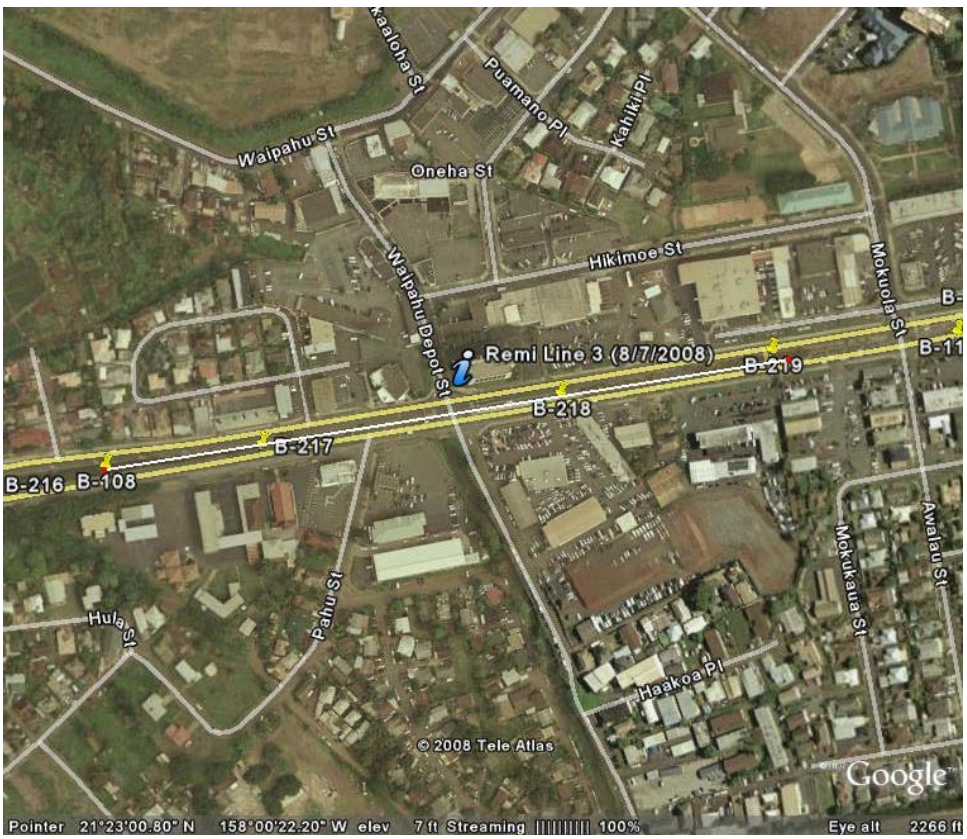

Figure 2: General 2D ReMi line location map - seismic line is white [showing date acquired] and geotechnical boreholes (e.g., B-217) shown with yellow markers [*Google Earth background image*].

Results from a portion of this line are presented in Figures 3a and 3b.

Instrumentation and Approach

Seismic ReMi data were acquired along the proposed HHCTCP site using a 24-channel Seismic Source DAQ LinkII seismograph. Analog signals from vertically-oriented geophones are collected in the DAQ seismograph where it is anti-alias filtered, converted to a digital signal, transmitted to the laptop. DAQ LinkII units have 24 channels; however, 48 receivers were placed on the ground along the survey line at 10 foot intervals to move along more rapidly in traffic. The receivers were 4.5-Hz low-frequency geophones, mounted on plates for the asphalt and concrete surface.

An active source was used, even though ReMi is a 'passive' technique, where the surface-wave source was placed off the end of the line. No timing was used for the source which thumped, idled and drove around to create surface wave energy. The backhoe was typically placed 30 to 60 m (100 to 200 ft) off the end of the line. Using a roll box, the 24 geophone array would increment by 4 receivers for each recording. Thus a 1D sounding was produced every 12.2 m (40 ft) along the line.

Data Processing

ReMi is a surface-wave technique that relates the Rayleigh-wave velocity to shear-wave velocity through an empirical relationship. That is, the ReMi method uses ambient noise, or vibrational energy that exists at a site without the use of input energy from hammers or explosives (like those used on refraction and reflection surveys) to model S-wave velocity. Ambient or vibrational energy can be anything from traffic to construction activities, tidal energy and microtremor earthquakes. The HHCTCP site was rich with all of these noise sources, and the backhoe added extra 'in-line' energy to produce high quality results.

For nearly all the sounding locations along the project corridor at least ten, unfiltered, 30-second ambient energy records were recorded using a 2 msec sample rate. In order to get through busy intersections quickly, only five 30-second records were acquired. For quality analysis purposes, records were collected with and without the backhoe source. It was found the backhoe greatly increased the frequency content of the recordings.

Noise records (including backhoe hits) collected at this site were processed using the SeisOpt® ReMi™ software, © Optim Inc., 2005 (Louie, 2001). Four processing steps were used to derive a 2D ReMi Vs profile:

Step 1: Generate a velocity spectrum from the (10) time series. This is a Fourier frequency analysis which plots slowness (*p*) versus frequency (*f*) curve (i.e., a *p-f curve*). The distinctive shape and slope of dispersive surface waves is an advantage of the p-f analysis because body waves and airwaves do not have dispersive (i.e., frequency dependent) velocity.

Step 2: Pick the Rayleigh-wave dispersion curve. The picks are made along the lowest edge of the *p-f* 'envelope' which bounds the dispersive-wave energy. Because higher-mode Rayleigh waves have phase velocities above those of the fundamental mode, the ReMi approach preferentially yields the fundamental-mode surface wave phase velocities (Pullammanappallil and others, 1993 and 1994).

Step 3: Model a shear wave velocity sounding. The ReMi method interactively forward-models the normal-mode dispersion data with a code adapted from Saito

(1979, 1988). The modeling iterates on phase velocity at each period (frequency). The analysis approach and the propagation properties of surface waves allow velocity reversals (e.g., a low Vs layer beneath a high Vs layer) to be successfully modeled.

Step 4: Generate 2D shear wave profiles. After a series of 1D soundings have been modeled, the data are entered into a smoothing algorithm that produces a 2D smooth-model of a series of 1D models.

The 2D profiles a cross-section of the subsurface with soundings spaced at 12.2 m (40 ft) for this project. A serious effort is taken during Step 4 to integrate geologic & geotechnical data. Soil stiffness (e.g., relative density from blow counts) and rock competency (e.g., from RQD), and depth that bedrock was encountered are important parameters for the 1D modeling in Step 3, and then generating 2D profiles.

Results

As might be expected for a data set that covers over 5 km (16,000 ft) of proposed HHTCP alignment, only a small sample of results can be presented here. Lines 3 and 4 provided some of the most dramatic and significant results from the project. Their results are included and discussed below.

ReMi profiles for data acquired along Line 3 are presented on Figures 3a and 3b. A portion of Line 4 is presented on Figures 4. The figures were created to allow comparison from line to line; that is, each figure uses the same color scale (i.e., Vs velocity), and horizontal to vertical exaggeration. Each figure presents only 231.6 m (760 feet) of 2D ReMi data. This length was determined by the geotechnical design team to be most useful for integration with plans and profiles. Stationing along the 'distance' axis is project stationing, and elevations were taken from profile drawings.

Geotechnical borings locations have been posted on the figures for integration of material property data with the S-wave velocity results. A few of the boring locations are approximate as they had not been drilled when the seismic survey was completed. Two velocity contour values have been identified on each cross-section: 1) a 183 meters per second (m/s) (600 feet per second - ft/s), a contour that represents the interpreted transition from undifferentiated *soft or loose* soil deposits to *stiff or d*ense soil deposits; and, 2) a 610 m/s (2,000 ft/s) contour that best depicts the top-of-bedrock. Respectively, the contour lines shown were selected based on: the IBC classification for *soft soils* (i.e., Vs < 600 ft/s); and, an average S-wave velocity for the *depth-to-bedrock* as determined from boreholes. Analysis of all the data indicated the average Vs of about 610 m/s (2000 ft/s) best represents the *velocity interface* between undifferentiated overburden / stiff soils and basalt at this site. The soil/bedrock interface, as described on the geologic logs of each borehole, shows a wide variation in the degree of weathering (e.g., *slightly- to highly-weathered*), as well as a significant difference in the fracture density (e.g., *moderately- to intensely-fractured*).

Clearly, closer inspection of each geotechnical boring log along the ReMi profiles produces an 'actual bedrock velocity' that ranges between about 550 to 730 m/s (1,800 and 2,400 ft/s). The correlation between the degree of weathering and fracture density and an increase or decreases of seismic-wave velocity in rock formations is well documented (i.e., Caterpillar Performance Handbook, Edition 35 - 2004, charts for rippability).

As previously described, ReMi is a seismic technique that averages the subsurface bulk properties beneath the receiver line (i.e., a 70 m or 230-feet,). Each sounding represents that bulk or average shear-wave velocity (processing Step 3). Using data acquired beneath over 350 soundings the smooth models shown on Figures 4 and 5 are the best representation of the depth to- and geometry of- the basalt contact between, below and beyond geotechnical drill hole control. As anticipated at this site, the ReMi data indicate significant variation and relief on the bedrock surface; additionally, there is considerable correlation between boring logs and bedrock depths as interpreted by 2D ReMi profiling.

As shown on Figures 3a and 3b, east of boring B-218 along the profile there is a definite deepening of the bedrock surface to greater than about 60 m (200 feet) beneath Station 64900 on Line 3. This trend is confirmed further east along Line 4 (Figure 4) at approximate station 65050 near borings B-109(SW) and B-110 (same location). The correlation of ReMi derived velocities with S-wave velocities measured in B-109(SW) using downhole Vs testing was very good. It defines the *soft soil* contact at about 13.7 m (45 feet). Note boring B-110 terminated at 54 m (~177 feet) bgs without encountering bedrock, which confirms the deep bedrock contact. Along this east end of Line 4 (Figure 4) the depth to bedrock determined by 2D ReMi imaging is the deepest within the survey area (approximately 70 m or 230 ft).

It should be noted that the 70 m (230 foot) depth is the absolute maximum resolvable depth with the field set-up and instrumentation used for this investigation. The true depth to bedrock may not be resolvable in this area, compared with other places along the line(s), because of the depth-to-bedrock and the wavelengths that could be measured using a 70.1m (230-foot) line length. However, the shape, size and approximate depth of this anomalously deep bedrock are substantiated by the data. As this long continuous profile continues east toward Line 5, bedrock slowly rises to less than about 30 m (100 feet) and continues to rise till the position of B-221 along Line 5 where the bedrock is within 3 m (10 feet) of the ground surface. Also shown on Figure 4 is a stretch beneath Line 4 where a very thick layer of *soft soil* (<183 m/s or 600 ft/s) was detected. The lateral variability and thickness of the soft soils was not anticipated at this site.

Conclusions

Acquisition of 2D seismic data along the HHCTCP project detected the presence of thick and laterally variable *soft soils*, as defined by the IBC standard, and also yielded good imaging of the soil/bedrock contact. The ReMi method was selected because of its ability to acquire seismic data in *very* noisy – high-traffic environments and to distinguish between saturated soils and basaltic bedrock based on their shear-wave velocity. The method is not affected by the presence of a shallow water table, which was important as much of the survey area was very near the coast. Correlation with geologic logs with low SPT blow counts in soft soil intervals and for depth-to-bedrock was very good. The seismic and geologic data show a relatively narrow range of S-wave velocities that could be appropriately interpreted as the soil/basalt contact. There appears to be some deep dense gravel with cobbles and boulders (e.g., a 'basal gravel unit') that could overlap the seismic velocity range interpreted as bedrock. The ReMi data clearly identify areas of thick soft soil deposits, in excess of 18.3 m (60 ft) thick using the S-wave velocity IBC classification between soft and stiff soils (<183 m/s or <600 ft/s). Boring logs and ReMi data collectively indicate that the basalt interface may be identified by velocities ranging from about 550 m/s (1,800 ft/s) if intensely weathered and highly fractured, to greater than 730 m/s (2,400 ft/s) in areas with lesser fracture density or little weathering at the soil/bedrock interface. Overall, the geometry of the bedrock surface, its relief and depth, was well defined by this seismic technique over long segments of the proposed HHCTCP site.

The method proved that it can be used when basaltic bedrock is shallow (e.g., 3 m bgs or10 feet), and when it is quite deep (60+ m bgs or 200+ ft bgs) with a 24-channel seismic set-up using a 70.1 m (230-foot) long spread. The use of a backhoe significantly added to the quality of the *p-f* curves and thus the ability to pick the surface-wave dispersion data. Quality of the ReMi data ranged from good to very good, which is directly attributed to the use of the backhoe and the tidal (low-frequency) energy present near the coast. Although the basaltic bedrock velocity clearly varies across the site, additional analysis of geotechnical data (if available) from borings regarding degree of weathering and fracture density would likely narrow the velocity range used to define depth-to-bedrock.

Acknowledgements

Zonge would like to thank Geolabs, Inc. whose support while in the field was invaluable. Additionally, we appreciate the input from the PB World geotechnical design team. Figures 3 and 4 are taken from the report specifications, and do not have SI units. These figures cannot be redrawn for publication purposes.

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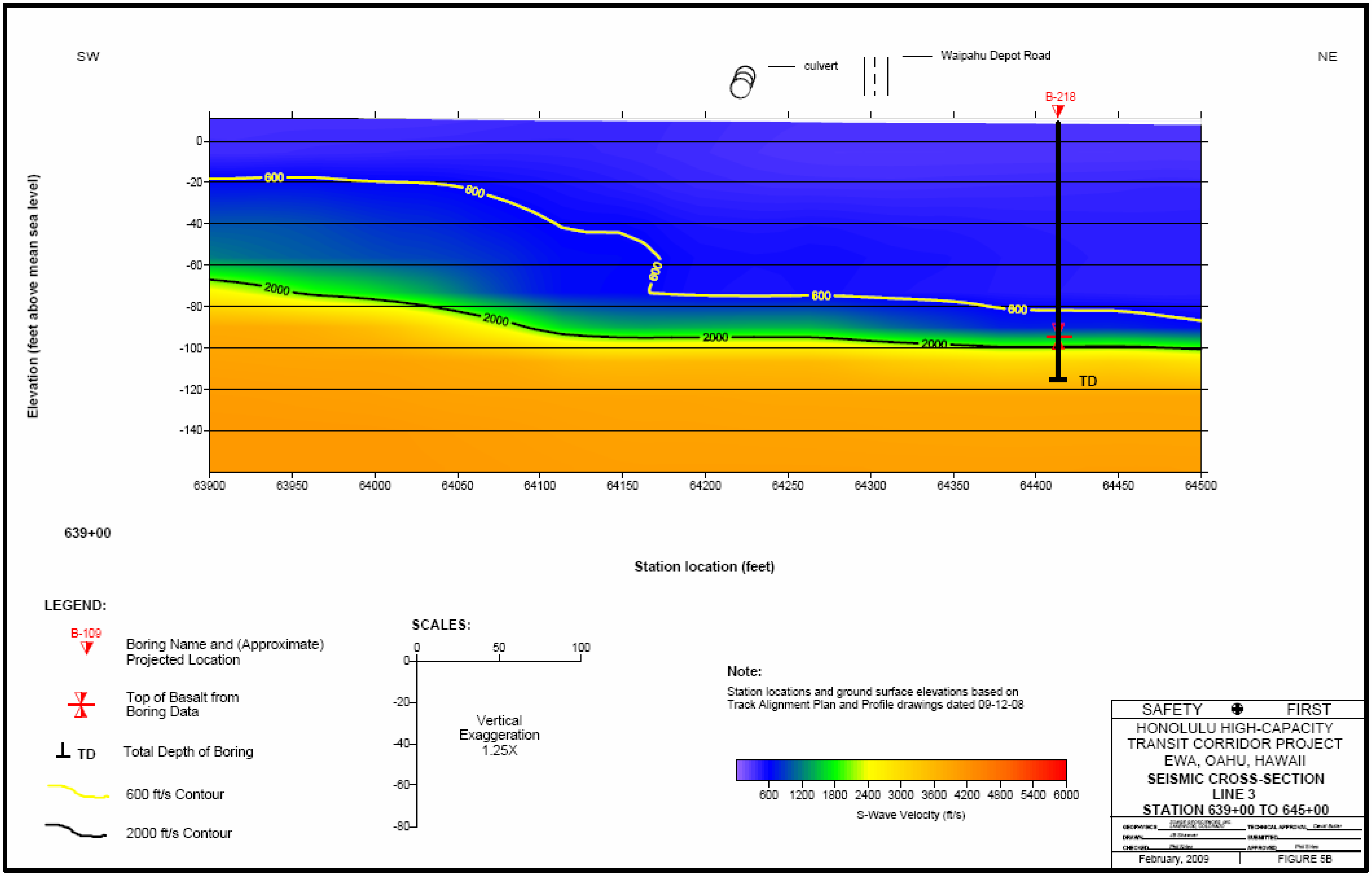

Figure 3a. 2D ReMi results from Line 3 (*continued on Figure 3b*).

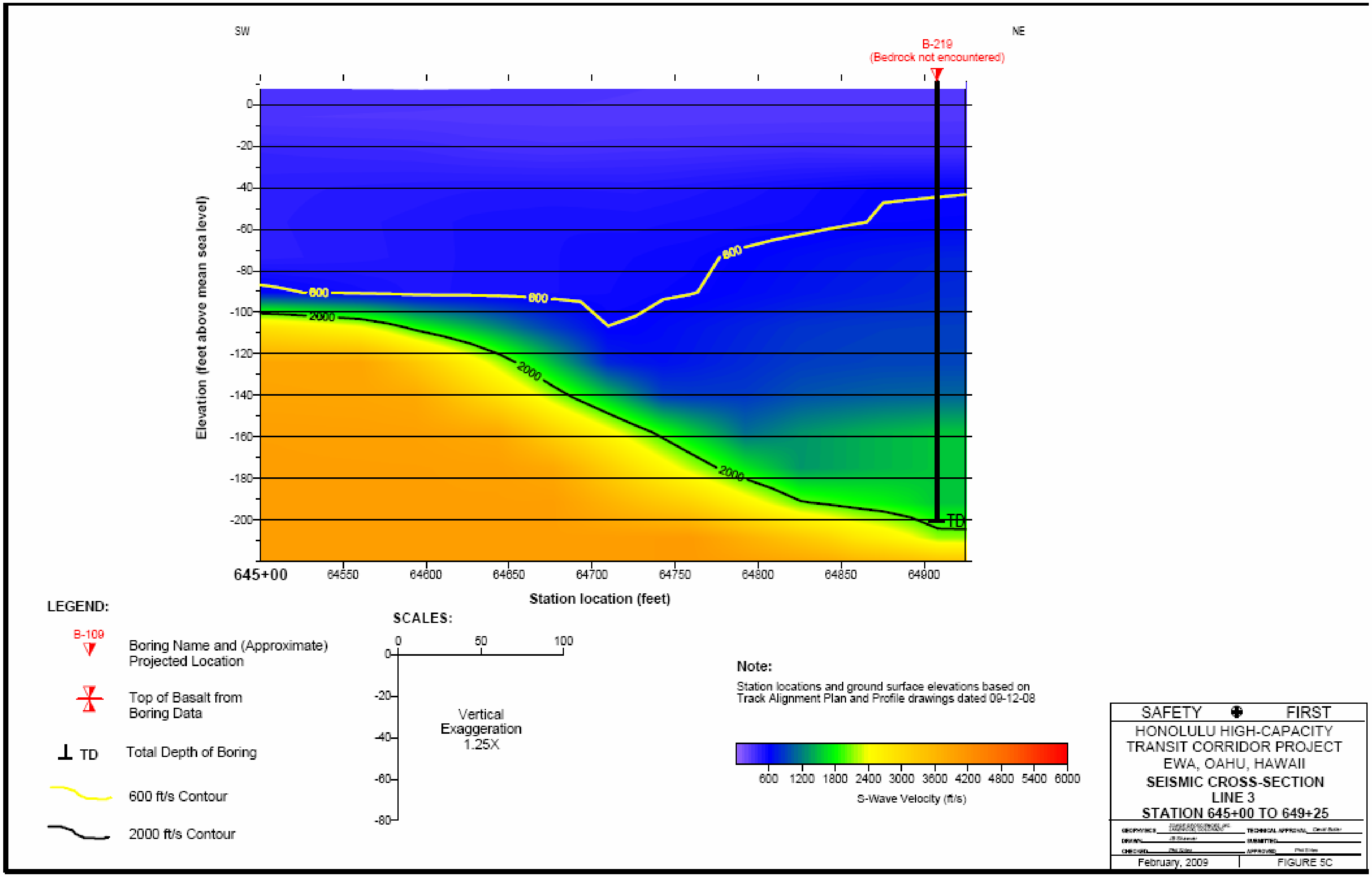

Figure 3b. 2D ReMi results from Line 3 (*continuation from Figure 3a*).

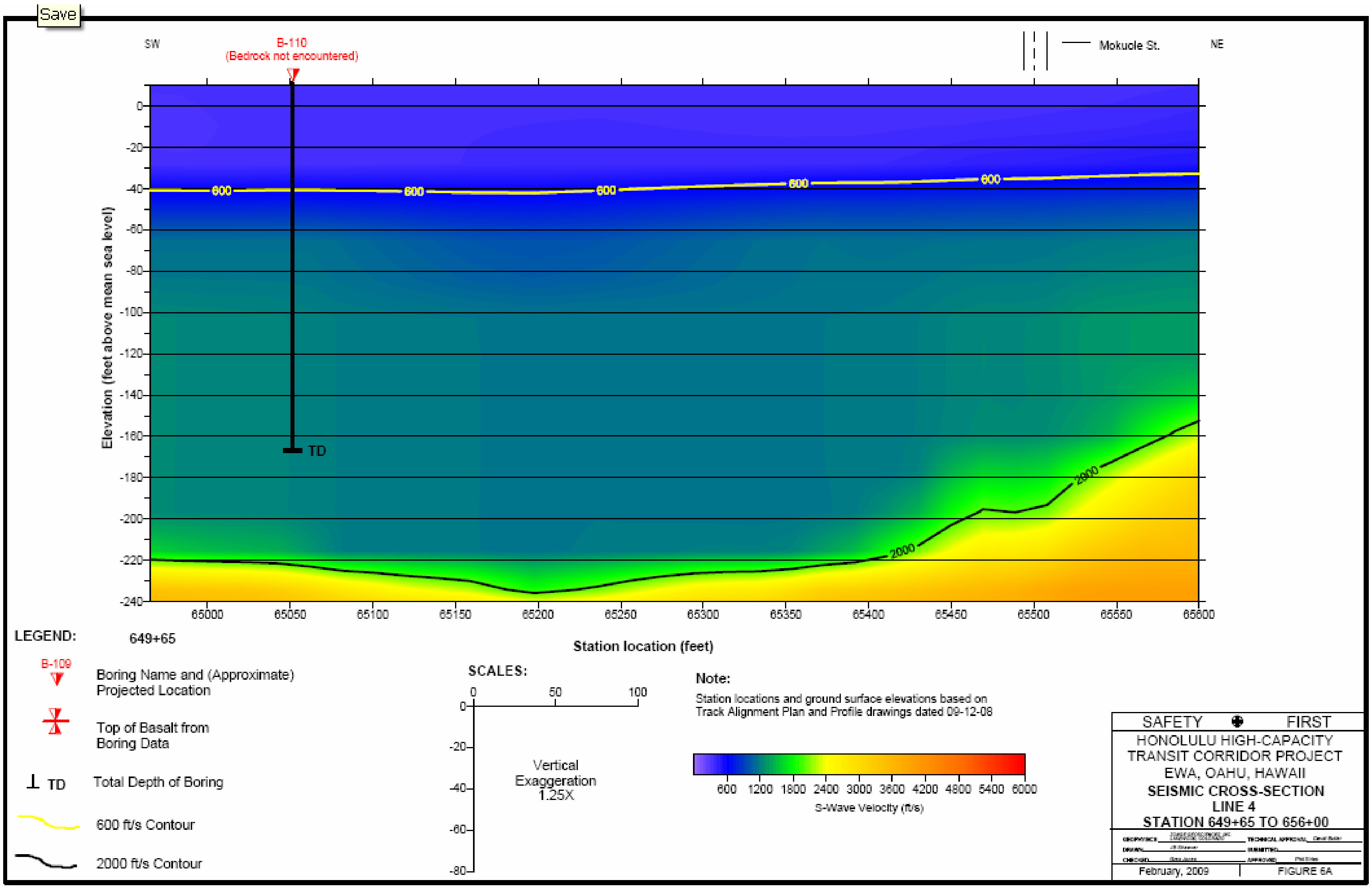

Figure 4. 2D ReMi results from a portion of Line 4 (*small portion of Line 4 only*).