RPT-2021-025, Rev 0

GEOPHYSICAL INVESTIGATION – TIERRA DEL MAR, OREGON

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Date Published
June 2021

Prepared for ERM

EXECUTIVE SUMMARY

A geophysical investigation, that included coincident electrical resistivity and multi-channel analysis of surface waves (MASW) data collection, was conducted at a property in Tierra Del Mar, Oregon to investigate a section of a HDD alignment. Three survey lines were collected; one survey line along the HDD alignment and two further survey lines spaced approximately 15 feet to the north and south, respectively. The objective of the geophysical investigation was to identify potential void space, cavities, or zones of weakness in the subsurface that could conceivably be related to recent HDD activities beneath the Tierra Del Mar shoreline.

These methods essentially provide two-dimensional (2D) cross-sectional information, which allows for a continuous and high-resolution evaluation of potential voids and sinkhole features. For the electrical resistivity method, the response we expect to observe in the model results will depend on the void type. Generally, air-filled voids present as more resistive targets compared to the background geology, and water-filled voids present as targets that are more conductive compared to the background geology. The response in the MASW model results would typically be a reduction in shear-wave velocity associated with the void features, with the method insensitive to the voids being air or water filled. Sometimes there will also be an increase in shear wave velocity above the reduction in shear-wave velocity, which is associated with increased stress of the materials bridging over the void. In a similar manner, we would expect a reduction in shear-wave velocity associated with sinkhole features and zones of weakness, compared to the surrounding unaffected geology.

There were no significant anomalies detected within the resolution limits of the electrical resistivity and MASW surveys that would indicate potential voids, cavities, or sinkhole features of concern along the survey lines relating to the HDD activities.

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LIST OF TERMS

Conductivity: The ability of a material to conduct an electrical impulse (in Siemen per meter, S/m); reciprocal of resistivity.

Inversion: Inversion, or inverse modeling, attempts to reconstruct subsurface features from a given set of geophysical potential measurements, and to do so in a manner that the model response fits the observations according to some measure of error.

Resistance: A measure of a material's ability to resist electrical current flow, in ohms.

Resistivity: A material property that is measured as its resistance to current per unit length for a uniform cross-section in ohm-meters.

1.0 INTRODUCTION

A geophysical investigation was performed by hydroGEOPHYSICS, Inc. (HGI) at a property in Tierra Del Mar, Oregon to investigate a section of a horizontal directional drilling (HDD) alignment. A potential sinkhole feature was recently discovered at the transition between the beach and sand dunes, located approximately above the HDD alignment. The geophysical survey was focused along an approximate 600 feet section of the HDD alignment from the punch in location, through the area of the sinkhole feature, and down the beach to approximately the low tide level. Three survey lines were collected; one survey line along the HDD alignment and two further survey lines spaced approximately 15 feet to the north and south, respectively.

1.1 OBJECTIVE

The objective of the geophysical investigation was to identify potential void space, cavities, or zones of weakness in the subsurface that could conceivably be related to recent HDD activities beneath the Tierra Del Mar shoreline. HGI used two geophysical methods to investigate the subsurface along the section of the HDD alignment. The first method was electrical resistivity, which helped to identify the different subsurface materials and the presence of any potential void spaces or cavities, and the potential development of sinkhole features. The second method was multichannel analysis of surface waves (MASW), which is a seismic method to help characterize the material stiffness to analyze the integrity of the area, and confirm any potential void and cavity locations or development of sinkhole features.

1.2 SCOPE OF WORK

The scope of the geophysical investigation included data acquisition over three coincident electrical resistivity and MASW survey lines. These methods essentially provide two-dimensional (2D) cross-sectional information, which allows for a continuous and high-resolution evaluation of potential voids and sinkhole features. For the electrical resistivity method, the response we expect to observe in the model results will depend on the void type. Generally, air-filled voids present as more resistive targets compared to the background geology, and water-filled voids present as targets that are more conductive compared to the background geology. The response in the MASW model results would typically be a reduction in shear-wave velocity associated with the void features, with the method insensitive to the voids being air or water filled. Sometimes there will also be an increase in shear wave velocity above the reduction in shear-wave velocity, which is associated with increased stress of the materials bridging over the void. In a similar manner, we would expect a reduction in shear-wave velocity associated with sinkhole features and zones of weakness, compared to the surrounding unaffected geology.

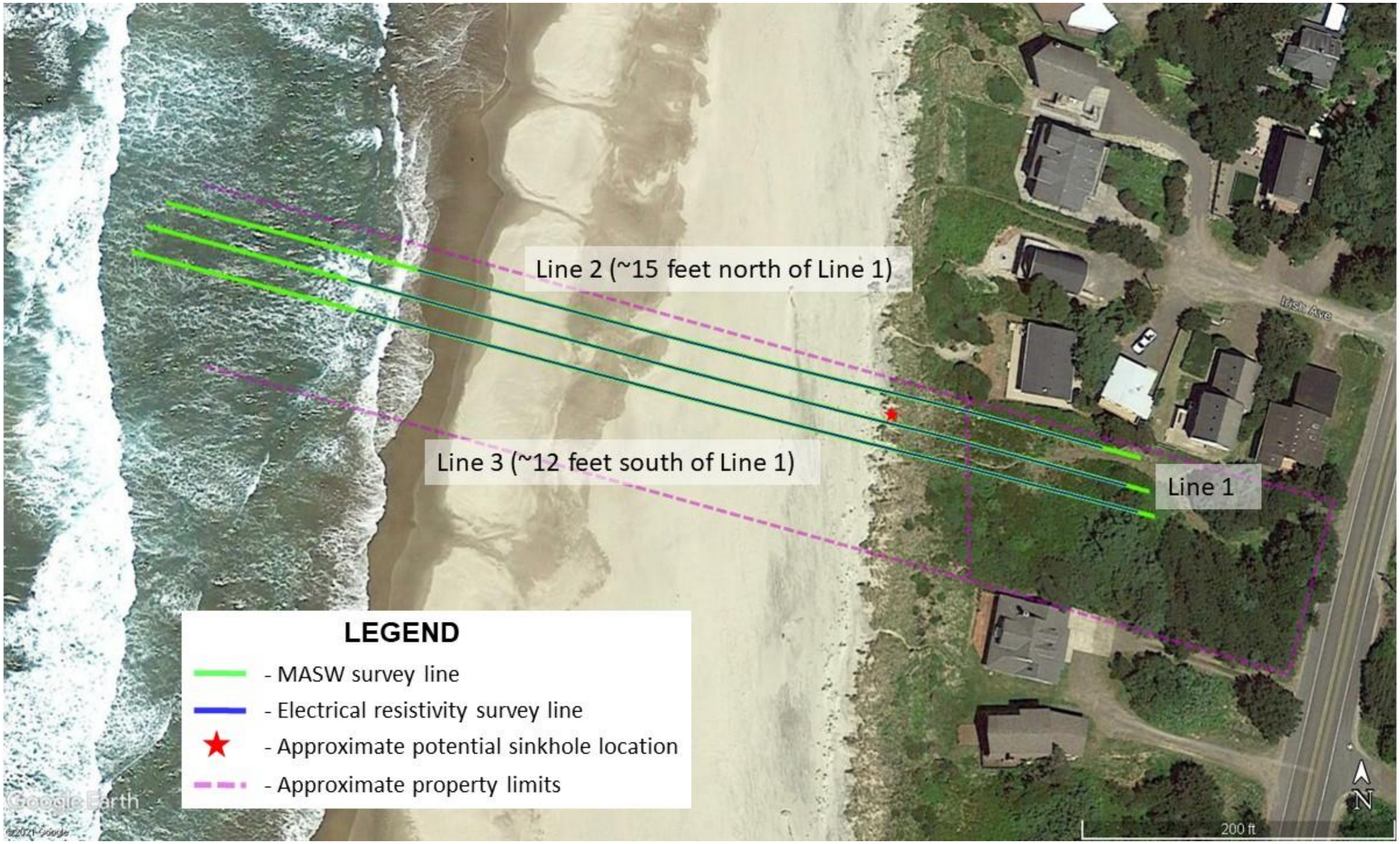
1.3 SURVEY LOCATION

The geophysical investigation was conducted on a vacant property in Tierra Del Mar, Oregon, which is located approximately 65 miles southwest of Portland, Oregon. Figure 1 displays an overview of the survey area location. Three coincident electrical resistivity and MASW survey line were acquired; one survey line along the HDD alignment and two further survey lines spaced approximately 15 feet to the north and south, respectively. Figure 2 displays the survey layout and the approximate location of the potential sinkhole feature.

Figure 1. Survey area overview.

Google Earth Imagery

Figure 2. Geophysical survey layout.

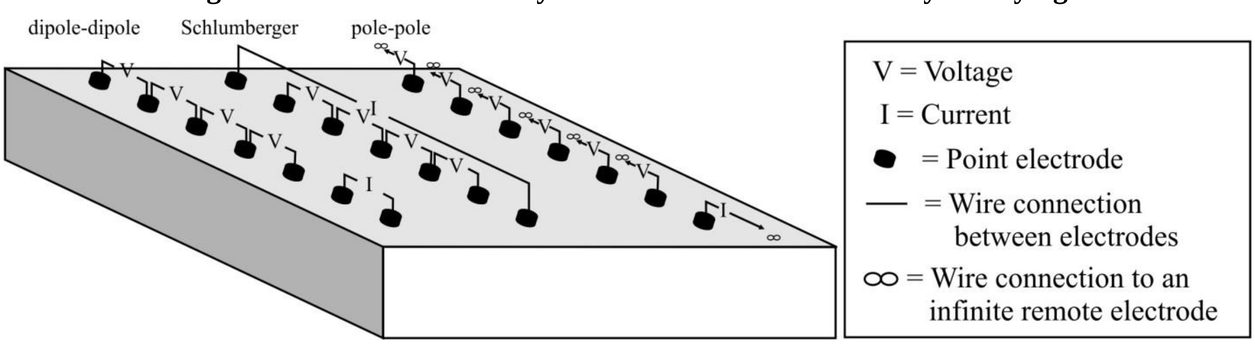


2.0 DESCRIPTION OF GEOPHYSICAL METHODS

2.1 ELECTRICAL RESISTIVITY

Electrical resistivity is a volumetric property that describes the resistance of electrical current flow within a medium (Rucker *et al.*, 2011; Telford *et al.*, 1990). Direct electrical current is propagated in rocks and minerals by electronic or electrolytic means. Electronic conduction occurs in minerals where free electrons are available, such as the electrical current flow through metal. Electrolytic conduction, on the other hand, relies on the dissociation of ionic species within a pore space. With electrolytic conduction, the movement of electrons varies with the mobility, concentration, and the degree of dissociation of the ions. Mechanistically, the resistivity method uses electric current (I) that is transmitted into the earth through one pair of electrodes (transmitting dipole) that are in contact with the soil. The resultant voltage potential (V) is then measured across another pair of electrodes (receiving dipole). Numerous electrodes can be deployed along a transect (which may be anywhere from feet to miles in length), or within a grid. Figure 3 displays examples of electrode layouts for surveying. The figure displays transects with a variety of array types (dipole-dipole, Schlumberger, pole-pole). A complete set of measurements occurs when each electrode (or adjacent electrode pair) passes current, while all other adjacent electrode pairs are utilized for voltage measurements. Modern equipment automatically switches the transmitting and receiving electrode pairs through a single multi-core cable connection. Rucker *et al.*, (2009) describe in more detail the methodology for efficiently conducting an electrical resistivity survey.

Figure 3. Possible arrays for use in electrical resistivity surveying.



The modern application of the resistivity method uses numerical modeling and inversion theory to estimate the electrical resistivity distribution of the subsurface given the known quantities of electrical current, measured voltage, and electrode positions. A common resistivity inverse method incorporated in commercially available codes is the regularized least squares optimization method (Loke *et al.*, 2003). The objective function within the optimization aims to minimize the difference between measured and modeled potentials (subject to certain constraints, such as the type and degree of spatial smoothing or regularization) and the optimization is conducted iteratively due to the nonlinear nature of the model that describes the potential distribution. The relationship between the subsurface resistivity (ρ) and the measured voltage is given by the following equation (from Dey and Morrison, 1979):

$$-\nabla \cdot \left[\frac{1}{\rho(x,y,z)} \nabla V(x,y,z) \right] = \left(\frac{I}{U} \right) \delta(x-x_s)\delta(y-y_s)\delta(z-z_s) \quad (1)$$

where I is the current applied over an elemental volume U specified at a point (x_s, y_s, z_s) by the Dirac delta function.

Equation 1 is solved many times over the volume of the earth by iteratively updating the resistivity model values using either the L_2-norm smoothness-constrained least squares method, which aims to minimize the square of the misfit between the measured and modeled data (Ellis & Oldenburg, 1994):

$$\left(J_i^T J_i + \lambda_i W^T W \right) \Delta r_i = J_i^T g_i - \lambda_i W^T W r_{i-1} \quad (2)$$

or the L_1-norm that minimizes the sum of the absolute value of the misfit:

$$\left(J_i^T R_d J_i + \lambda_i W^T R_m W \right) \Delta r_i = J_i^T R_d g_i - \lambda_i W^T R_m W r_{i-1} \quad (3)$$

where g is the data misfit vector containing the difference between the measured and modeled data, J is the Jacobian matrix of partial derivatives, W is a roughness filter, R_d and R_m are the weighting matrices to equate model misfit and model roughness, Δr_i is the change in model parameters for the i^{th} iteration, r_i is the model parameters for the previous iteration, and λ_i = the damping factor.

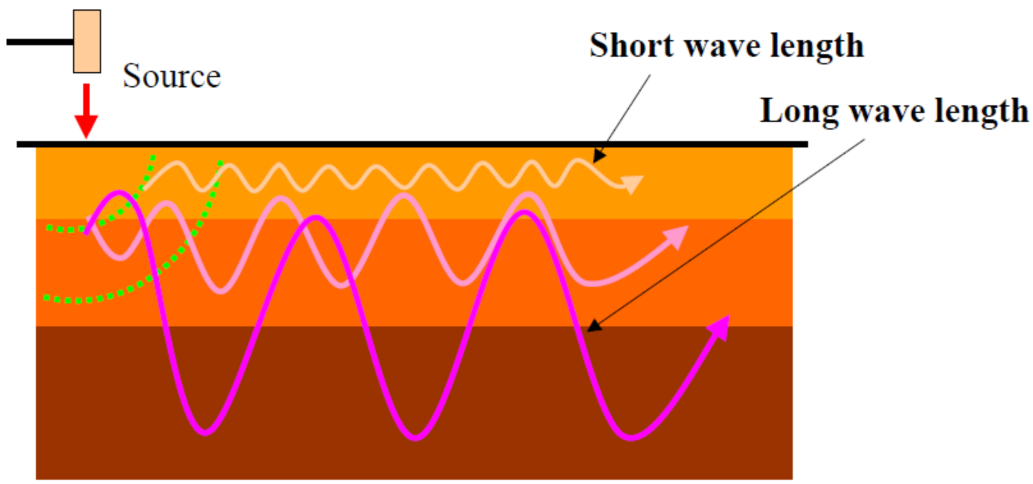
2.2 MASW

Dispersion, or change in phase velocity with frequency, is the fundamental property utilized in surface-wave seismic methods. Phase velocity of surface-waves is sensitive to the shear wave velocity (Vs); phase velocity of surface-waves is typically 90-95% that of the shear wave velocity. Surface wave dispersion can be significant in the presence of velocity layering, which is common in the near-surface environment. There are other types of surface waves, or waves that travel along a surface, but in this application we are concerned with the Rayleigh wave, which is also called "ground roll" since the Rayleigh wave is the dominant component of ground roll.

"Active source" surface-wave surveying means that seismic energy is intentionally generated at a specific location relative to the geophone spread and recording begins when the source energy is imparted into the ground. This is in contrast to "passive source" surveying, also called "microtremor" surveying or "refraction microtremor" (or the commercial term "ReMi") surveying, where there is no time break and motion from ambient energy (generated by cultural noise, wind, wave motion, etc. at various, and usually unknown, locations relative to the geophone spread) is recorded. Only the active source technique was used for this survey effort.

Surface-wave energy decays exponentially with depth beneath the surface. Longer wavelength (that is, longer-period and lower-frequency) surface waves travel deeper and thus contain more information about deeper velocity structure (Figure 4). Shorter wavelength (that is, shorter-period and higher-frequency) surface waves travel shallower and thus contain more information about shallower velocity structure. In this context, by their nature and proximity to the geophone spread, it can be said that higher-frequency active source surface waves resolve the shallower velocity structure and lower-frequency passive source surface waves resolve the deeper velocity structure.

Figure 4. Example of surface wave dispersion produced during a MASW survey.



MASW surveys are conducted using the same source and seismograph equipment as the more common P-wave seismic refraction surveys, requiring only a change to lower frequency geophones (typically 4.5Hz). They are much easier to conduct than shear wave surveys, and benefit from increasing source power efficiency (for each sledgehammer blow 67% of the energy produced is in the form of surface-waves, 26% shear waves, and 7% P-waves) and consequently improved signal-to-noise ratio. The technique works best in soft rock geology conditions with minimal or constant topography change across the spread.

Shear wave velocity is one of the elastic constants and is closely related to Young's modulus. Under most circumstances, shear wave velocity is a direct indicator of the ground strength (stiffness) and therefore can be used to derive load-bearing capacity.

3.0 METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

Data acquisition consisted of three coincident electrical resistivity and MASW survey lines; one survey line along the HDD alignment and two further survey lines spaced approximately 15 feet to the north and south, respectively. Data acquisition occurred from May 20th to May 23rd, 2021, and included set-up, data acquisition, and cleanup. The field crew consisted of two people.

3.1.1 Detailed Coverage

Total geophysical survey coverage over the Tierra Del Mar property and shoreline equaled approximately 1,620 linear feet of electrical resistivity and 2,105 linear feet of MASW. For the electrical resistivity acquisition, electrodes were installed at a constant spacing of approximately 6.5 feet (2 meters) along the survey lines. The overall length of each survey line and additional coverage information is detailed in Table 1. For the MASW acquisition, geophones were installed at a constant spacing of approximately 5 feet (1.5 meters) along the survey lines. The overall length of each survey line and additional coverage information is detailed in Table 2. A detailed coverage map of the electrical resistivity and MASW survey line locations is displayed in Figure 2. Electrode and geophone locations were surveyed using a handheld Garmin handheld global positioning system (GPS) unit by HGI.

3.2 DATA ACQUISITION

3.2.1 Electrical Resistivity

Data were collected using a SuperSting™ R8 multichannel electrical resistivity system (Advanced Geosciences, Inc. [AGI], Texas) and associated cables, electrodes, and battery power supply. The SuperSting™ R8 meter is commonly used in surface geophysical projects and has proven itself to be reliable for long-term, continuous acquisition. The stainless steel electrodes were laid out along lines with a constant electrode spacing (~6.5 feet/2 meters). Multi-electrode systems allow for automatic switching through preprogrammed combinations of four electrode measurements.

3.2.2 MASW

Two Geode Ultra-Light Exploration 24–Channel Seismographs (Geometrics, Inc., San Jose, California) were used for MASW surveying, providing a total of 48-channels. 4.5-Hz geophone placement was every 5 feet, and using a shot point offset of 40 feet from the end geophone (a number of off-end shot point distances, or offsets, were tested at each line location to determine the optimum offset to use). The seismic source consisted of a 16-pound sledgehammer striking a polyethylene plate. The seismographs were controlled from a laptop in order to view each shot to ensure acceptable data quality, and record and process the data. Additional shots with the source forming a new "stack" of data were added until the desired data quality was achieved. The shot record (seismogram) was also saved to the computer and stored for subsequent processing. A real-time noise monitor showing all active geophones was carefully scrutinized during shots to ensure that noise levels were at a minimum for each shot. This included watching for breaks in wind noise, construction and other traffic, and other sources of noise.

Table 1. Electrical resistivity survey details.

Line #	Start Position (UTM Zone 10, meters)		End Position (UTM Zone 10, meters)		Electrode Spacing (feet)	Total # of Electrodes	Length (feet)	Acquisition Date (2021)
	Easting	Northing	Easting	Northing				
1	424111.86	5010950.57	423953.19	5010995.97	6.6	84	545	5/21
2	424107.47	5010958.19	423967.60	5010997.92	6.6	74	480	5/23
3	424113.41	5010944.96	423955.15	5010989.36	6.6	83	538	5/23

Coordinates surveyed using a handheld Garmin GPS unit with typical accuracy level of ±3 meters

Table 2. MASW survey details.

Line #	Start Position (UTM Zone 10, meters)		End Position (UTM Zone 10, meters)		Geophone Spacing (feet)	Total # of Geophones	Length (feet)	Acquisition Date (2021)
	Easting	Northing	Easting	Northing				
1	424116.71	5010949.25	423910.08	5011008.15	5	141	705	5/20
2	424115.37	5010955.99	423913.99	5011013.17	5	137	685	5/20-5/21
3	424116.96	5010944.24	423907.27	5011002.59	5	144	715	5/22

Coordinates surveyed using a handheld Garmin GPS unit with typical accuracy level of ±3 meters

3.3 DATA PROCESSING

3.3.1 Electrical Resistivity

3.3.1.1 Quality Control

The geophysical data for the resistivity survey, including measured voltage, current, measurement (repeat) error, and electrode position, were recorded digitally with the AGI SuperSting R8 resistivity meter. Quality control, both in-field and in-office, was performed throughout the survey to ensure data quality passed accepted standards and to assure quality of data before progressing the survey. Following onsite QC, the data were transferred to the HGI server for storage and detailed data processing and analysis.

3.3.1.2 Resistivity Processing

Data removal was performed based on degree of noise/other erroneous data. During data removal, those data that appeared to be extremely noisy and fell outside the normal range of accepted conditions were manually removed within an initial Excel spreadsheet analysis. Examples of conditions that would cause data to be removed include, negative or very low voltages, high-calculated apparent resistivity, extremely low current, and high repeat measurement error. No resistivity data values were manipulated or changed, such as with smoothing routines or box filters; noisy data were only removed from the general population. The final edited datasets were formatted for input into the 2D inverse modeling software.

3.3.1.3 2D Resistivity Inversion

RES2DINVx64 software (Geotomo, Inc.) was used for inverting individual lines in two dimensions. RES2DINV is a commercial resistivity inversion software package available to the public from www.geotomosoft.com. The inversion process followed a set of stages that utilized consistent inversion parameters to maintain consistency between each model. Inversion parameters were chosen to maximize the likelihood of convergence. Inversion parameter choices included the starting model, the inversion routine (robust or smooth), the constraint defining the value of smoothing and various routine halting criteria that automatically determined when an inversion was complete. Convergence of the inversion was judged whether the model achieved an absolute error of less than 5% within three to five iterations. If convergence was not achieved during the first inversion run, a filter run was initiated using a filtered dataset based on high error for measured versus modeled data, not to exceed 10% data removal per filter run. The data quality for the three survey lines did not require filtering.

The data were inverted with appropriate topography. The inverted data were output from RES2DINV into an XYZ data file and were then gridded and color contoured in Surfer (Golden Software, Inc.).

3.3.2 MASW

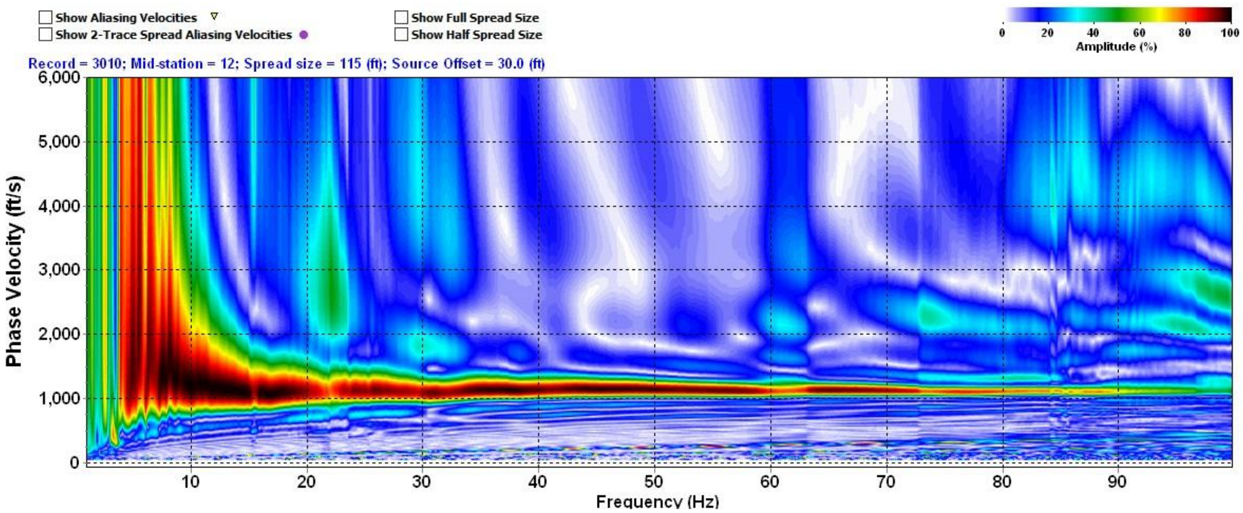
3.3.2.1 Quality Control

Data were given a preliminary assessment for quality control (QC) in the field to assure quality of data before progressing the surveys. Following onsite QC, all data were transferred to the HGI server for storage and detailed data processing and analysis. Data quality was inspected and checked for consistency, and data files were saved to designated folders on the server. Records of survey configuration, location, equipment used, environmental conditions, proximal infrastructure or other obstacles, and any other useful information were recorded during data acquisition and were saved to the HGI server.

3.3.2.2 MASW Processing

The data processing flow for the MASW analysis used the SurfSeis (Kansas Geological Survey, Lawrence, Kansas) MASW processing software. The processing sequence included: encoding the field geometry, generating dispersion images (example shown in Figure 5), extracting dispersion curves, and inversion of the dispersion curves using a gradient-based iterative approach, with the goal of minimizing the RMS error between the observed and calculated velocity curves. The inversion produces a cross section of shear wave velocity as a function of depth, generally ranging between 300 to 5000 feet/second. The quality of the inversion is judged by its convergence achieving an RMS of less than 10% within five to seven iterations.

Figure 5. Example dispersion curve.



General soil classifications from the National Earthquake Hazards Reduction Program (NEHRP) are shown in Table 3. The table assumes an average of the shear-wave velocity (Vs) over the top 100 feet.

Table 3. NEHRP soil classification for 100-foot average shear-wave velocity.

Site Class	Soil Profile	Shear Wave Velocity (feet/sec)
A	Hard Rock	Vs > 5000
B	Rock	2500 < Vs < 5000
C	Very Stiff Soil / Soft Rock	1200 < Vs < 2500
D	Stiff Soil	600 < Vs < 1200
E	Soft Soil	Vs < 600

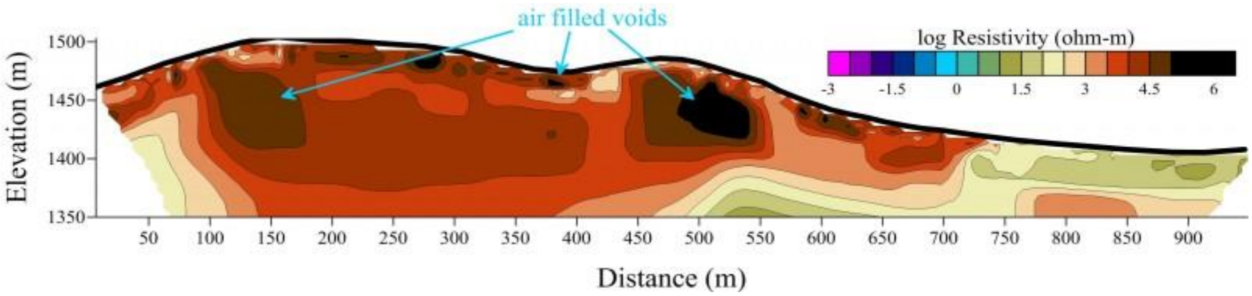
4.0 RESULTS

The inverse model results for the electrical resistivity and MASW survey lines are presented as two-dimensional (2D) profiles in Figures 7 through 9. A common color contouring scale is used for each method across all of the survey lines to highlight any features that may be indicative of potential void features and to provide the ability to compare intensity of targets from survey line to survey line. For the electrical resistivity profiles, electrically conductive (low resistivity) subsurface regions are represented by cool hues (pink through blue shades) and electrically resistive regions are represented by warm hues (orange through brown shades). For the MASW profiles, low shear-wave velocity is represented by cool hues (purple through blue shades) and high shear-wave velocity is represented by warmer hues (orange through red shades). Other notes of interest about the site, either observed by or relayed to HGI, are also annotated on the profiles.

The objective of the survey was to geophysically characterize areas that indicate features potentially representative of subsurface voids, cavities, or sinkhole features. Therefore, in the case of air-filled voids, the targets for the electrical resistivity survey would be regions of high resistivity (low conductivity) based on the assumption that the void space would have increased resistivity compared to the surrounding bedrock material. The case for water- or sediment-filled voids would differ significantly, since the fluid or sediment filling the voids would likely be more conductive than the surrounding bedrock. Therefore, the potential voids or cavities that are either backfilled/partially filled with sediment, grout, groundwater, or seawater would likely be regions of low resistivity (high conductivity).

The contrast in resistivity between the native material and subsurface voids will depend on a number of factors, including the depth to the voids, the fill material of the void (air, water, sediment, or a mixture), dimensions of the void, and the nature of the bedrock material (massive, fractured, weathered). An example of an electrical resistivity survey HGI performed looking for subsurface voids over the Kartchner Caverns State Park in Arizona is shown in Figure 6. The known air filled voids show up as resistive features, displaying resistivity values of the order of 1,000's to 10,000's of ohm-meters (Ωm), within a background of limestone bedrock, displaying resistivity values of 100's of Ωm. There is a fair amount of variability in resistivity value depending on the dimensions of and depths to the subsurface voids. The background material in this example is moderately resistive, similar to the majority of bedrock material. Another point to consider is that the resolution of the electrical resistivity technique will decrease with depth, as with all surface based geophysics. Thus as the imaging depth increases the sampling volume of the electrical resistivity technique may become too large to detect these contrasts unless the void spaces are of significant size (10's feet).

Figure 6. Electrical Resistivity Profile over the Kartchner Caverns State Park, AZ. The Air Filled Voids and the Caverns and Passageways show up as Resistive Features in the more Conductive Limestone Bedrock Background.



The response in the MASW model results would typically be a reduction in shear-wave velocity associated with the void features, with the method insensitive to the voids being air or water filled. Sometimes there will also be an increase in shear wave velocity above the reduction in shear-wave velocity, which is associated with increased stress of the materials bridging over the void. In a similar manner, we would expect a reduction in shear-wave velocity associated with sinkhole features and zones of weakness, compared to the surrounding unaffected geology.

4.1 LINE 1 RESULTS

Figure 7 displays the electrical resistivity and MASW model results for Line 1, which was collected in an east to west direction but has the profile distances flipped to display west to east. Line 1 was approximately positioned over the HDD alignment, running alongside the concrete vault access to the punch in location.

In general, the electrical resistivity model results display a highly conductive near-surface on the western half of the profile, likely representing the salt water in the subsurface. At approximately 250 feet along the profile, the near-surface layer transitions to more resistive materials, likely representing fresher groundwater and the unsaturated zone. Below an elevation of approximately -35 feet above mean sea level (amsl), the model results become predominantly homogeneous, with a resistivity value range of approximately 25 to 40 Ωm ($\log_{10}$ resistivity value range of 1.4 to 1.6). The MASW model results display a low shear-wave velocity upper layer, which is approximately 50 feet in thickness. The shear-wave velocity increases sharply, to above 1,000 feet/sec, across the interface to an underlying higher shear-wave velocity layer.

Overall, there does not appear to be any significant anomalies, within the resolution limits of the two methods, which would indicate potential voids, cavities, or sinkhole features of concern along this survey line relating to the HDD activities. We have highlighted a number of features of interest in the profiles that contrast to the general conditions described above, including:

- We observe a near-surface conductive region in the electrical resistivity model results, located between approximately 35 and 70 feet along the profile, around the location of the concrete vault (labeled (a) in Figure 7). This is likely a response to the concrete structure and the associated disturbance of the ground during the excavations and backfilling activities in this area. The MASW model results display a low shear-wave velocity layer in the same location, likely a response to the disturbed ground due to the activities associated with the concrete vault construction and HDD actvities.

- We observe a number of highly conductive regions in the electrical resistivity model results, located between approximately 35 and 290 feet along the profile and generally located on the lower edges of the model results (labeled (b) in Figure 7). Of these regions, there are a number of localized highly conductive regions between approximately 35 and 130 feet along the profile, that extend from the area below the concrete vault location towards the west. The conductivity of these regions would tend to suggest that they are responses to the metal casing and infrastructure associated with the HDD, based on the proximity to the punch in location for the drilling activities. The MASW model results display a subtle reduction in shear-wave velocity in the general area associated with the conductive regions, between approximately 70 and 120 feet along the MASW profile (labeled (b) in Figure 7). This could be a response to the HDD activities weakening the materials in this area compared to the surrounding undisturbed areas.

- The region associated with the location of the inadvertent return, and associated excavated pit, along this survey line displays a more conductive nature than the surrounding areas in the electrical resistivity model results. The conductive region is closely related to the impacted area on the ground surface, located between approximately 95 and 115 feet along the profile (labeled (c) in Figure 7). Below this near-surface region, there is a break in the resistivity contours, with generally more conductive values, as compared to the surrounding areas, extending to an elevation of approximately -30 feet amsl. This conductive, approximately vertical, structure is relatively narrow, at approximately 10 to 15 feet wide, and extends to the overlaid HDD alignment (labeled (c) in Figure 7). This feature could be a response to the effect of the drilling mud and represent a preferential pathway this material took when it migrated from the drill hole to the surface. If this is the case, this could suggest that the drilling mud was isolated to this limited aerial extent between the drill hole and ground surface. The MASW model results display a low shear-wave velocity region at the ground surface in the location of the inadvertent return, which is likely a response to the excavated pit and less consolidated backfill (labeled (c) in Figure 7). Directly below this the MASW profile displays a region with increased shear-wave velocity, as compared to the surrounding area, that could be a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments (labeled (c) in Figure 7).

- A similar conductive region is observed in the electrical resistivity model results between approximately 140 and 160 feet along the profile, and between an elevation of approximately -20 and -25 feet amsl (labeled (d) in Figure 7). The MASW model results display an increase in shear-wave velocity in the coincident location, as compared to the surrounding area, that could be a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments (labeled (d) in Figure 7).

- In the area associated with the sand dunes and transition to the beach, where the observed potential sinkhole was located, we observe a number of isolated highly resistive regions in the electrical resistivity model results. These are located at approximately 125, 140, and 165 feet along the profile, and generally within approximately 5 to 10 feet of the ground surface (labeled (e) in Figure 7). Based on the likely unsaturated nature of the sediments at this elevation, this could be a response to a potential air-filled void in the near surface. We do not observe a reduction in the shear-wave velocity of the materials in coincident locations in the MASW model results for the regions located at approximately 125 and 165 feet along the electrical resistivity profile, likely indicating the lack of any potential void space. There is a very subtle decrease in the shear-wave velocity of the coincident location to the region located at approximately 140 feet along the electrical resistivity profile (labeled (e) in Figure 7). This could indicate this region is associated with a potential small void space or sinkhole feature, although there is no indication that this has migrated from deeper in the subsurface, and therefore a direct cause of the HDD activities, based on the contours in the electrical resistivity and MASW profiles. Alternatively, this is likely a response to a coarser grained region of the sand dunes, which would tend to be more resistive and potentially less consolidated.

- Once we transition to the beach the electrical resistivity model results quickly become dominated by the influence of the highly conductive salt water. We do observe some structure to the interface between the fresher groundwater and salt water, at approximately 275 feet along the profile, that could indicate some preferential pathways for the various groundwater types in the subsurface (labeled (f) in Figure 7). However, it is unlikely that the subtle features associated with potential voids and sinkholes would be discernable in this area. The MASW model results are not impacted by the presence of water, fresh or salt, in the subsurface and so we do not observe the same drop off in resolution of the targets of interest towards the ocean. Over the same section, the MASW profile tends to indicate a low shear-wave velocity near-surface layer, likely indicating the unconsolidated sands on the beach. Immediately below this, there is a predominantly continuous stiffer layer, with higher shear-wave velocity, that is approximately 10 feet in thickness, which overlies another low shear-wave velocity layer of variable thickness. Below an elevation of approximately -50 feet amsl the shear-wave velocity gradually increases with depth to the imaging depth limit of the model results. The deeper low shear-wave velocity layer tends to be laterally continuous and therefore seems unlikely to represent isolated void space or sinkhole features developing from impacts of the HDD activities in this area. In addition, there is no significant decrease in shear-wave velocity that extends down to the depth of the HDD alignment that indicate the propagation of void or sinkhole features towards the surface.

4.2 LINE 2 RESULTS

Figure 8 displays the electrical resistivity and MASW model results for Line 2, which was collected in an east to west direction but has the profile distances flipped to display west to east. Line 2 was located approximately 15 feet to the north of and parallel to Line 1. The electrical resistivity survey line was truncated due to the tide state at the time of the survey being higher than for the previously collected Line 1 survey.

In general, the electrical resistivity model results display a similar structure to that observed in the Line 1 model results, including a highly conductive near-surface on the western half of the profile, likely representing the salt water in the subsurface. At approximately 300 feet along the profile, the near-surface layer transitions to more resistive materials, likely representing fresher groundwater and the unsaturated zone. Below an elevation of approximately -30 feet above mean sea level (amsl), the model results become predominantly homogeneous, with a resistivity value range of approximately 16 to 40 Ωm ($\log_{10}$ resistivity value range of 1.2 to 1.6). The MASW model results display a low shear-wave velocity upper layer, which is approximately 50 feet in thickness. The shear-wave velocity increases sharply, to above 1,000 feet/sec, across the interface to an underlying higher shear-wave velocity layer.

Overall, there does not appear to be any significant anomalies, within the resolution limits of the two methods, which would indicate potential voids, cavities, or sinkhole features of concern along this survey line relating to the HDD activities. We have highlighted a number of features of interest in the profiles that contrast to the general conditions described above, including:

- We observe a number of highly conductive regions in the electrical resistivity model results, located between approximately 60 and 240 feet along the profile and generally located on the lower edges of the model results (labeled (g) in Figure 8). Of these regions, there are a number of localized conductive regions between approximately 60 and 145 feet along the profile, that extend from the area associated with the concrete vault location towards the west. The conductivity of these regions would tend to suggest that they are responses to the metal casing and infrastructure associated with the HDD, based on the proximity to the punch in location for the drilling activities. The MASW model results display a subtle reduction in shear-wave velocity in the general area associated with the conductive regions, between approximately 70 and 130 feet along the MASW profile (labeled (g) in Figure 8). This could be a response to the HDD activities weakening the materials in this area compared to the surrounding undisturbed areas.

- Once again, the region associated with the location of the inadvertent return, and associated excavated pit, along this survey line displays a more conductive nature than the surrounding areas in the electrical resistivity model results. The conductive region is closely related to the impacted area on the ground surface, located between approximately 125 and 145 feet along the profile (labeled (h) in Figure 8). Below this near-surface region, there is a break in the resistivity contours, with generally more conductive values, as compared to the surrounding areas, extending to an elevation of approximately -20 feet amsl. This conductive, approximately vertical, structure is relatively narrow, at approximately 10 to 15 feet wide, and extends beyond the overlaid HDD alignment to approximately the underlying conductive regions that are thought to be related to the HDD alignment (labeled (h) in Figure 8). This feature could be a response to the effect of the drilling mud and represent a preferential pathway this material took when it migrated from the drill hole to the surface. If this is the case, this could suggest that the drilling mud was isolated to this limited aerial extent between the drill hole and ground surface. Therefore, the lateral extent of the inadvertent return extends out to at least the location of Line 2 to the north, or at least the electrical resistivity method is sensitive to this effect at this location. The MASW model results display a low shear-wave velocity region at the ground surface in the location of the inadvertent return, which is likely a response to the excavated pit and less consolidated backfill (labeled (h) in Figure 8). Directly below this the MASW profile displays a region with increased shear-wave velocity, as compared to the surrounding area, that could be a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments. The increased shear-wave velocity region does not display the same vertical extent as evident in the Line 1 model results and may suggest the inadvertent return is more focused along the Line 1 alignment at the depth of the drilling.

- An additional conductive region is observed in the in electrical resistivity model results between approximately 90 and 100 feet along the profile, and between an elevation of approximately -2 and -8 feet amsl (labeled (i) in Figure 8). The MASW model results display a subtle increase in shear-wave velocity in the coincident location, as compared to the surrounding area, that could be a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments (labeled (i) in Figure 8). However, the region of increased shear-wave velocity tends to extend to the east and deeper into the profile and while the electrical resistivity model results do indicate a conductive feature deeper in the profile, they do not appear to display significant connectivity.

- In the area associated with the sand dunes and transition to the beach, where the observed potential sinkhole was located, the electrical resistivity model results display a more continuous layering of highly resistive material. This likely represents the unsaturated unconsolidated sands of the dunes and upper beach area. We do not observe any significant reduction in the shear-wave velocity of the materials in coincident locations in the MASW model results. Therefore, there does not appear to be any indications for potential void space or sinkhole development in this area of the profile.

- Once we transition to the beach the electrical resistivity model results quickly become dominated by the influence of the highly conductive salt water. We do observe some structure to the interface between the fresher groundwater and salt water, at approximately 300 feet along the profile, which could indicate some preferential pathways for the various groundwater types in the subsurface (labeled (j) in Figure 8). However, it is unlikely that the subtle features associated with potential voids and sinkholes would be discernable in this area. Over the same section, the MASW profile tends to indicate a low shear-wave velocity near-surface layer, likely indicating the unconsolidated sands on the beach. Immediately below this, there is a semi continuous stiffer layer, with higher shear-wave velocity, that is approximately 10 feet in thickness, which overlies another low shear-wave velocity layer of variable thickness. The transition from this layer to the underlying high shear-wave velocity layer, which extends to the imaging depth limit of the model results, displays a higher degree of undulation in the interface than Line 1. There is one region, between approximately 190 and 245 feet along the MASW profile and at an elevation of approximately -30 feet amsl, that displays a significant decrease in shear-wave velocity compared to the surrounding materials (labeled (k) in Figure 8). The location of this region corresponds to the overlaid HDD alignment and could be a response to some form of disturbance from the drilling activities in the subsurface, potentially a void space or the development of a weak zone. There is no obvious coincident feature in the electrical resistivity model results. This region does appear to be isolated, and at depth, likely indicating no propagation of the potential void space or sinkhole feature towards the ground surface.

4.3 LINE 3 RESULTS

Figure 9 displays the electrical resistivity and MASW model results for Line 3, which was collected in an east to west direction but has the profile distances flipped to display west to east. Line 3 was located approximately 12 feet to the south of and parallel to Line 1 (Line 3 was positioned to avoid significant impact to the natural vegetation and revegetation efforts on site).

In general, the electrical resistivity model results display a similar structure to that observed in the previous two survey line model results, including a highly conductive near-surface on the western half of the profile, likely representing the salt water in the subsurface. At approximately 295 feet along the profile, the near-surface layer transitions to more resistive materials, likely representing fresher groundwater and the unsaturated zone. Below an elevation of approximately -30 feet above mean sea level (amsl), the model results become predominantly homogeneous, with a resistivity value range of approximately 16 to 40 Ωm (log_{10} resistivity value range of 1.2 to 1.6). The MASW model results display a low shear-wave velocity upper layer, which is approximately 50 feet in thickness. The shear-wave velocity increases sharply, to above 1,000 feet/sec, across the interface to an underlying higher shear-wave velocity layer.

Overall, there does not appear to be any significant anomalies, within the resolution limits of the two methods, which would indicate potential voids, cavities, or sinkhole features of concern along this survey line relating to the HDD activities. We have highlighted a number of features of interest in the profiles that contrast to the general conditions described above, including:

- We observe a number of highly conductive regions in the electrical resistivity model results, located between approximately 55 and 240 feet along the profile and generally located on the lower edges of the model results (labeled (l) in Figure 9). Of these regions, there are a number of localized conductive regions, namely centered on approximately 60 and 110 feet along the profile, that extend from the area associated with the concrete vault location towards the west. The conductivity of these regions would tend to suggest that they are responses to the metal casing and infrastructure associated with the HDD, based on the proximity to the punch in location for the drilling activities. The MASW model results display a subtle reduction in shear-wave velocity in the coincident region associated with the conductive feature at approximately 110 feet along the electrical resistivity profile (labeled (l) in Figure 9). This could be a response to the HDD activities weakening the materials in this area compared to the surrounding undisturbed areas. However, we observe an increase in shear-wave velocity in the coincident region associated with the conductive feature at approximately 60 feet along the electrical resistivity profile (labeled (m) in Figure 9). This could simply indicate stiffer, stronger natural sediments in this region or the impact of the drilling activities was minimal to the surrounding area in this location.

- Once again, the region associated with the location of the inadvertent return, and associated excavated pit, along this survey line displays a more conductive nature than the surrounding areas in the electrical resistivity model results. The conductive region is closely related to the impacted area on the ground surface, located between approximately 120 and 140 feet along the profile (labeled (n) in Figure 9). This conductive region extends to an elevation of approximately -20 feet amsl, creating a vertical break in the resistivity contours in this location. This feature could be a response to the effect of the drilling mud and represent a preferential pathway this material took when it migrated from the drill hole to the surface. If this is the case, this could suggest that the drilling mud was isolated to this limited aerial extent between the drill hole and ground surface. Therefore, the lateral extent of the inadvertent return extends out to at least the location of Line 3 to the south, or at least the electrical resistivity method is sensitive to this effect at this location. The MASW model results display a low shear-wave velocity region at the ground surface in the location of the inadvertent return, which is likely a response to the excavated pit and less consolidated backfill (labeled (n) in Figure 9). Directly below this the MASW profile displays a region with increased shear-wave velocity, as compared to the surrounding area, that could be a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments (labeled (n) in Figure 9). The increased shear-wave velocity region is not as significant as evident in the Line 1 model results and may suggest the inadvertent return is of limited aerial extent along the Line 1 alignment at the depth of the drilling.

- In the area associated with the sand dunes and transition to the beach, where the observed potential sinkhole was located, the electrical resistivity model results display a more continuous layering of highly resistive material. This likely represents the unsaturated unconsolidated sands of the dunes and upper beach area. We do not observe any significant reduction in the shear-wave velocity of the materials in coincident locations in the MASW model results. Therefore, there does not appear to be any indications for potential void space or sinkhole development in this area of the profile.

- Once we transition to the beach the electrical resistivity model results quickly become dominated by the influence of the highly conductive salt water. We do observe some structure to the interface between the fresher groundwater and salt water, at approximately 300 feet along the profile, which could indicate some preferential pathways for the various groundwater types in the subsurface (labeled (o) in Figure 9). However, it is unlikely that the subtle features associated with potential voids and sinkholes would be discernable in this area. Over the same section, the MASW profile tends to indicate a low shear-wave velocity near-surface layer, likely indicating the unconsolidated sands on the beach. Immediately below this, there is a semi continuous stiffer layer, with higher shear-wave velocity, that is approximately 10 feet in thickness, which overlies another low shear-wave velocity layer of variable thickness. Below an elevation of approximately -50 feet amsl the shear-wave velocity gradually increases with depth to the imaging depth limit of the model results. The deeper low shear-wave velocity layer tends to be laterally continuous and therefore seems unlikely to represent isolated potential void space or sinkhole features developing from impacts of the HDD activities in this area. In addition, there is no significant decrease in shear-wave velocity that extends down to the depth of the HDD alignment that could indicate the propagation of potential void or sinkhole features towards the surface.

Figure 7. Coincident electrical resistivity and MASW model results for Line 1.

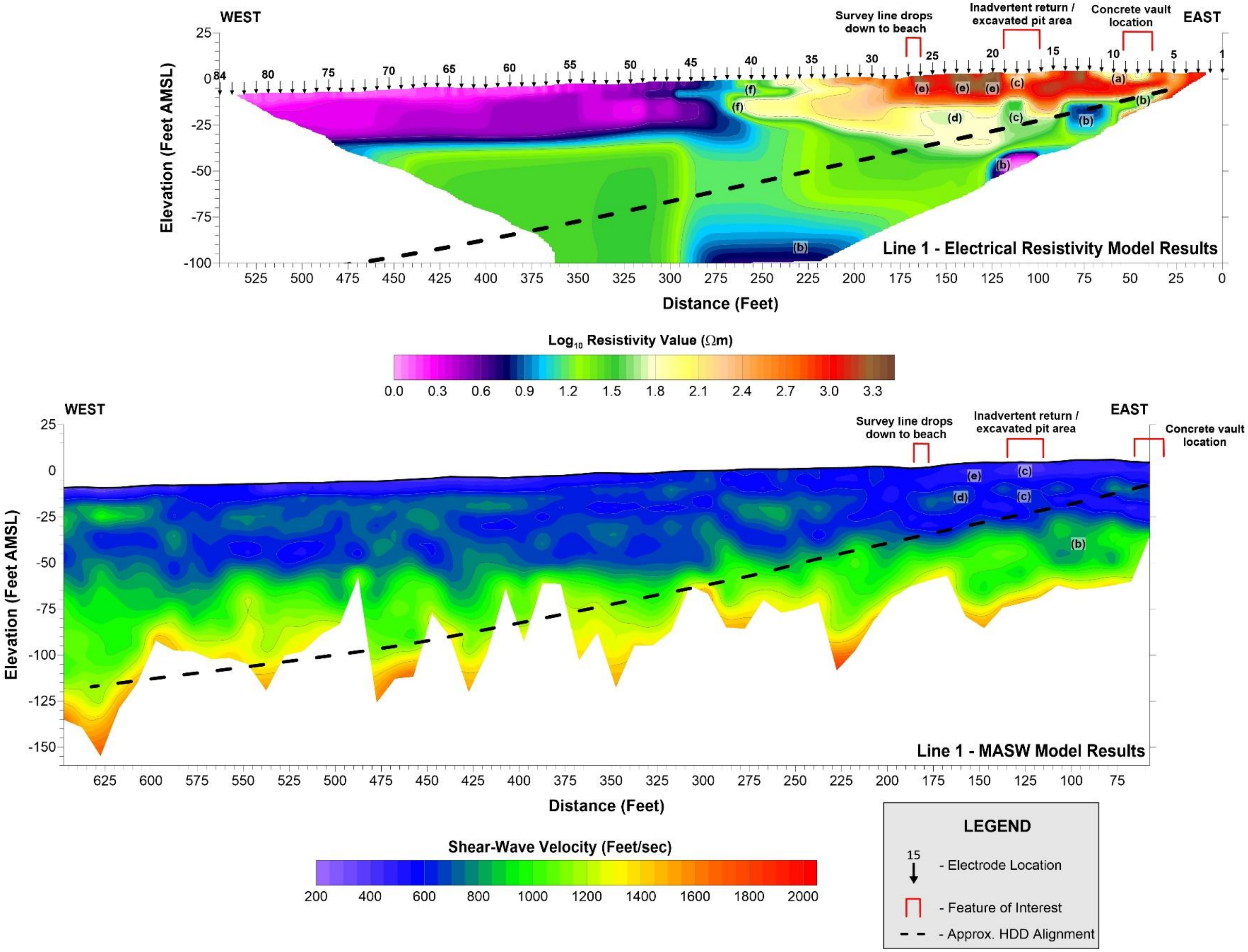


Figure 8. Coincident electrical resistivity and MASW model results for Line 2.

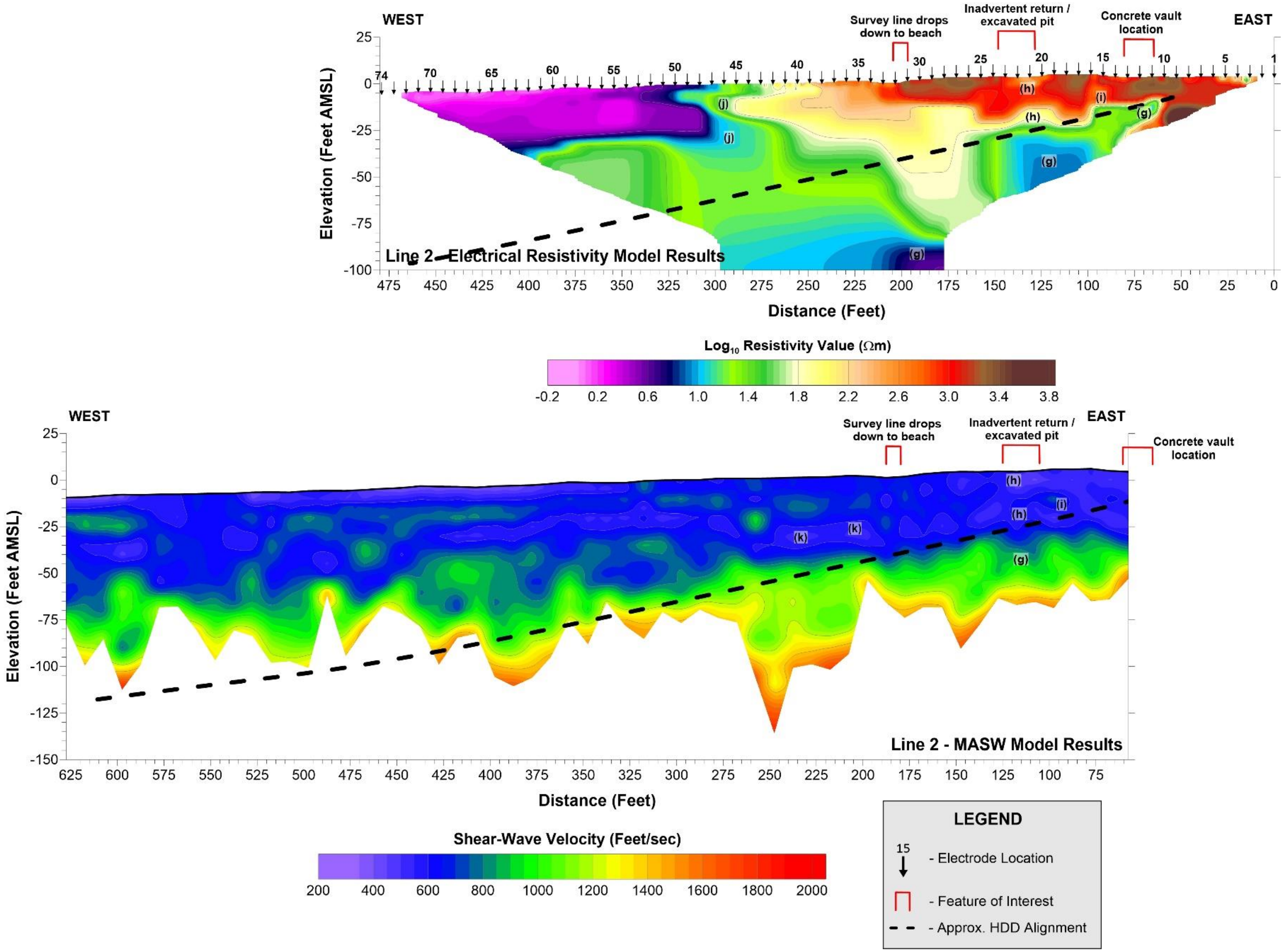
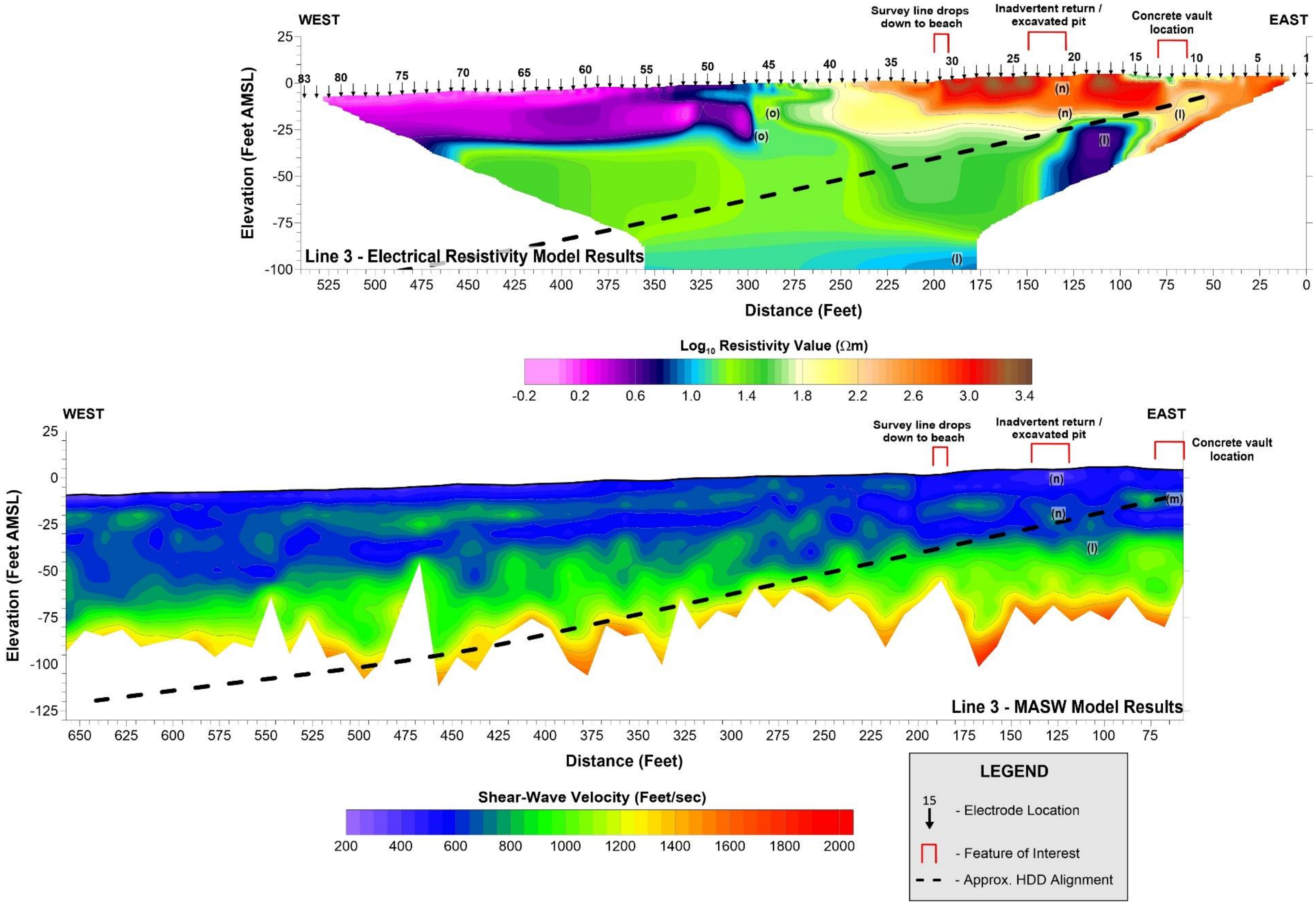


Figure 9. Coincident electrical resistivity and MASW model results for Line 3.



5.0 CONCLUSIONS

A geophysical investigation, that included coincident electrical resistivity and MASW data collection, was conducted at a property in Tierra Del Mar, Oregon to investigate a section of a HDD alignment. Three survey lines were collected; one survey line along the HDD alignment and two further survey lines spaced approximately 15 feet to the north and south, respectively. The objective of the geophysical investigation was to identify potential void space, cavities, or zones of weakness in the subsurface that could conceivably be related to recent HDD activities beneath the Tierra Del Mar shoreline.

The three electrical resistivity survey lines displayed a number of highly conductive regions along the lower edge of the model results, beginning in the area of the concrete vault marking the punch in location and extending to the west. The conductivity of these regions would tend to suggest that they are responses to the metal casing and infrastructure associated with the HDD, based on the proximity to the punch in location for the drilling activities. In general, these features are associated with regions displaying lower shear-wave velocity in the MASW model results, which could be a response to the HDD activities weakening the materials in this area compared to the surrounding undisturbed areas.

In addition, all three electrical resistivity survey lines display a conductive response in and below the area associated with the inadvertent return, and associated excavated pit. The conductive region extends down to the overlaid HDD alignment and would tend to suggest a preferential pathway for the drilling mud to the ground surface. The pathway appears to be limited in lateral extent and focused to a small volume immediately below the impacted area on the surface. The response is more subtle in Lines 2 and 3, suggesting the majority of the conductive drilling mud was confined to a pathway predominantly below Line 1. The associated response observed in the MASW model results generally displays a low shear-wave velocity feature in the near-surface, likely reflecting the excavated pit and less consolidated backfill. An increase in shear-wave velocity is observed deeper in the subsurface, potentially a response to the materials becoming stiffer or more consolidated due to the effect of the drilling mud infiltrating the sediments.

There were no significant anomalies detected within the resolution limits of the electrical resistivity and MASW surveys that would indicate potential voids, cavities, or sinkhole features of concern along the survey lines relating to the HDD activities.

6.0 REFERENCES

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