ADVANCEMENTS IN SUBSURFACE MODELING USING SEISMIC REFRACTION DATA

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Abstract

Standard geophysical survey practice using seismic refraction techniques has predominantly produced two-dimensional cross sections of the subsurface. The state-of-the-practice for nearly three decades has been to process refraction data with layer reconstruction techniques using the generalized reciprocal method, time-intercept and other similar techniques. Within the past decade, advancements in the computer technology and the development of tomographic modeling algorithms have greatly increased the ability to detect subsurface anomalous features, increase lateral and vertical resolution, and provide better graphical presentation of the data. Recently, 2D finite-element modeling of seismic data has proven successful to image discrete anomalies such as voids.

This paper presents recent developments in a new approach for processing refraction data, the presentation of subsurface data, and the use of these data after geophysical modeling is complete. The approach adapts numerical modeling using the discrete element method and particle flow code (DEM-PFC). The procedure is termed the *Geostructural Analysis Package (GAP)* which, in its initial stages of development has been optimized for geotechnical applications, such as 2D and 3D seismic refraction data processing and presentation on engineering projects. Although GAP has not been primarily created for seismic refraction, this paper will illustrate significant advancement in refraction data processing. Currently, using GAP for seismic applications represents an innovative approach that includes improved data analysis processes and produces more functional result for the end users. For the application illustrated in this paper the end users are typically civil or geotechnical engineers. The value of using this approach for seismic applications is its ability to produce 2D, 2.5D and 3D models to assist engineers or geologists extract additional information from the geophysical data (e.g., material properties), or perform static and dynamic stress analysis. This paper makes the point that mapping the top of bedrock may be the *objective* of a geophysical survey, but it is not the engineering *purpose* for the site investigation (e.g., construction of a critical facility, design of a foundation for a structure, etc.). With high-quality calibrated 2D, 2.5D and 3D DEM-PFC *models*, not geophysical *images*, engineers are more likely to use the seismic results by incorporating them directly into their engineering analyses.

Results from two case histories are presented showing the benefit of assessing seismic refraction data using the DEM-PFC numerical modeling approach. In the first example, standard 2D refraction data were analyzed and the interpolated results were presented as a 3D model. The second example is a 3D surface tomography reconstruction of four slightly offset 2D refraction shot lines.

Introduction

Conventional seismic refraction *'first-arrival time'* data have been processed and presented utilizing a number of methods for a very long time. Palmer's (1981) approach using the generalized reciprocal method (GRM) has been the industry standard for assessing a layered earth using first (refracted) arrival times of body wave energy to produce images of the subsurface. It has been effective, proven, and incredibly valuable as a method to analyze refraction data. Similarly, over the past decade multiple refraction tomography algorithms have been developed as the 'next generation tool' for data analysis, presentation and visualization of refraction data. These newer, more complex mathematical approaches, all termed tomography, vary to some degree in their analysis, but the image results are generally comparable (Sheehan, 2005). In either case, GRM or tomography, the analyses produce two dimensional (2D) images of the subsurface. These 2D images represent the geophysical results provided to the engineers (for example) for the next phase of site investigation or design. More recently, 2D finite difference modeling of wave propagation has successfully demonstrated the strength of using numerical modeling as an approach to analyze elastic wave propagation and deformation (Saenger, et. al., 2000; and Saenger, et. al. 2004). Gelis (2005) was particularly successful applying finite difference modeling as a means of using surface–wave energy to detect shallow cavities and create 2D models.

The purpose of this paper is to introduce a new approach to analyze seismic refraction data. Clearly, GRM, refraction tomography, and 2D finite difference models each have their value, strengths, and weaknesses (like all geophysical data analysis methods). The goal is to continue promulgating surface seismic investigations using refraction field techniques, and additionally offer alternative means to fully address the purpose of the engineering or environmental application. Not all field programs need advanced numerical modeling to process seismic data, but when complex geologic environments or engineering problems carry high risk associated with the results, more sophisticated and robust approaches may be required.

Numerical modeling using discrete element method (DEM) code is not new (Zhang and others, 1995; Zhang and others, 1996; and, Zhang, 1996). However, optimizing the advantages offered by the numerical modeling codes (either FEM or DEM) to create a more comprehensive modeling package is a significant advancement. The advantage of FEM over DEM is its ability to efficiently work with continuum under static conditions. The advantages gained though the use of DEM analysis is its ability to deal with discontinuities and manage element interactions in dynamic models. FEM and DEM techniques can each support these separate capabilities, although rather inefficiently and with significant limitations.

Integrating DEM numerical modeling with particle flow code (PFC) is an approach to discretize earth or man-made material models, deform them in a dynamic mode, and manage the complex interaction of the system. The practical nature of this comprehensive modeling package, called GAP (Sirles, et. al. 2005) allows the material properties and interlocking mechanisms to interact. The sensible aspect that numerical modeling affords in a 3D geologic world is the unique opportunity to view materials and their interactions in 3D. The result of optimizing DEM and PFC for seismic applications is greater accuracy, faster speed for data processing, less memory requirements for the hardware, higher resolution of subsurface material characteristics, and more functionality for the output results. That is, results of numerical modeling produce 2D, 2.5D and 3D model not simply *images*. They are calibrated ground simulations (Rock and Zhang, 2002).

The GAP DEM-PFC code has been used to perform forward or inverse modeling for various geotechnical applications. Through two case histories presented herein, the approach and value of producing results in models (versus images) will be shown. The Micro Model Method is similar in some ways to what was developed by Itasca (1999 and 2003) in the approach they call particle flow code. GAP and PFC use the same fundamental element interaction equations used in DEM. Therefore, the mathematical approach uses well established numerical modeling techniques. The current version of GAP has been optimized for seismic wave propagation, for both forward and inverse modeling. It supports tomographic and holographic inversion, and soon will support full-waveform seismic inversion. The full-waveform inversion module is currently under development. The package, in its current form, includes a wide range of built-in digital signal processing capabilities, such as filtering, automatic first arrival-time picking, and common source/receiver comparison in 3D geometry. The modeling uses a rapid consolidation algorithm developed by Dr Runing Zhang (1996). This modeling package can model geotechnical materials such as rock, soil, dry or wet sand, construction materials such as wood, steel, and concrete, or fluids. It can model the interaction between different materials, including solids and fluids, friction, and other interlocking mechanical systems. The ability to model discontinuities such as cracks, distinct layers, and blocks of arbitrary shape, including dynamic crack propagation is a distinct advancement. It is efficient for both static load analysis and dynamic simulation. Modeling very small-strain deformations such as seismic wave energy, up to large deformations such as mine subsidence or slope failure can also be performed.

The GAP code is the most comprehensive numerical modeling and seismic analysis program, that was developed over the past year, for practical near-surface engineering and environmental applications. Because GAP is not a refraction *imaging* package, the following paragraphs were included to shed light on the breadth this technology has beyond the refraction application presented here. That is, the code is being used to model chemical processes, and supports modeling cement hydration in concrete (Rock, et. al, 2005). This includes modeling the thermodynamics of heat flow from the heat of hydration generated during the concrete curing process, and heat transfer to the surrounding environment. The DEM-PFC technology is being developed further to model ground water flow, membranes for geosynthetics, MSE-type retaining walls, and thin supports systems such as soil nails, roof bolts, and rebar (Rock, *in progress*).

Using numerical modeling, this approach can support numerous boundary conditions for stress analysis, including static and dynamic vertical and lateral loads. Similarly, dynamic constraints for seismic analysis are supported and static and dynamic simulations can also be easily generated. Extensive front-end user interface for model initialization has been developed allowing complex geological formations and structures to be quickly constructed (in 2D or 3D). Geologic features such as faults, voids, cracks, layers, karstic bedrock, radical ground surface topography, lakes, and rivers can be integrated into the model. Man-made structures can be quickly generated, including reinforced concrete, rockery walls, piles, shafts, and tunnels for other geotechnical applications. In the seismic application, a distinct advantage of the DEM-PFC method is the ability to process as many source/receiver positions as necessary to meet the project objectives. Source and receiver arrays can be either on the ground surface or in a crosshole configuration. Positional accuracy of sources and receivers is very important to produce calibrated earth models.

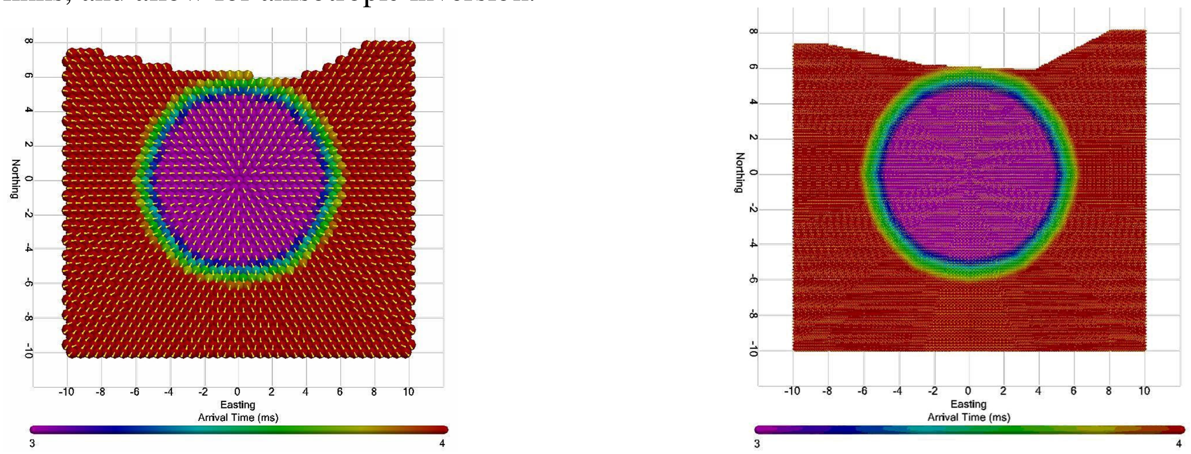
The back-end data visualization and reporting capabilities are very useful for the end users of the data. Various material properties such as velocity, stress, compression, acceleration, displacement, material density, and cracking, can be displayed. This is accomplished by using different palettes, contouring, slicing (not just horizontal or vertical slices); and of course, rotating, translating, or enlarging the resultant model volume. Any combination of materials, velocity ranges, stress ranges, etc, can be hidden or displayed. Output into animated slide presentations (e.g., Microsoft PowerPoint), AVI movie files, or complete MS Word documents (reports with figures, captions, and text) have been automatically generated through the GAP process.

Several seismic techniques have implemented the GAP process such as crosshole tomography, crosshole sonic logging, and surface refraction. Applications vary from bedrock mapping, determinng layer thickness and stiffness, volume calculations, geotechnical boring interpolation, driven pile assessment, rockery walls with wedge-type failure, assessment of drilled shaft integrity, concrete curing, slope stability, rock fall barrier evaluation, and avalanche modeling. The two geotechnical case histories illustrated in this paper are fully integrated field programs implementing parts of the GAP numerical modeling process.

Approach

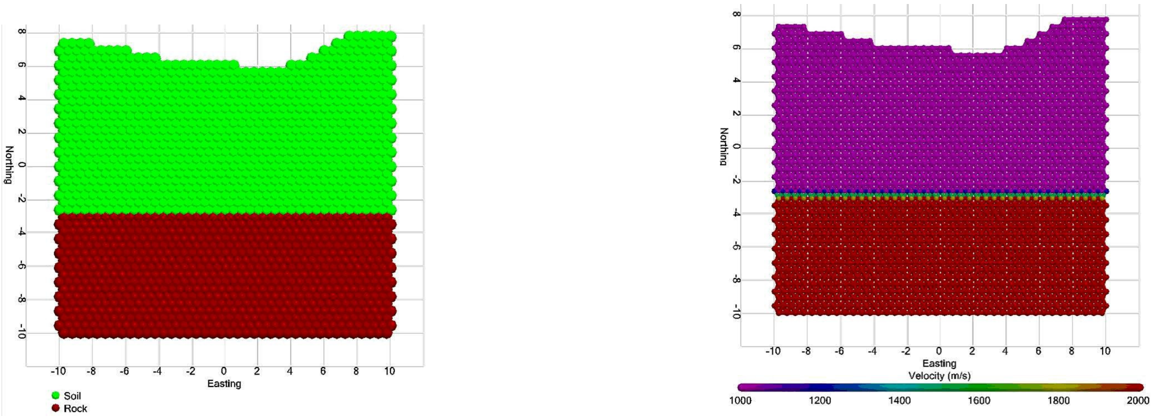
The approach to using the DEM-PFC technique can best be illustrated through a series of diagrams or models. The model is made up of what can be thought of as a system of *elements* and *links*. The discrete elements can be described as a set of spherical elements, or balls. Each ball has it own property (e.g., velocity), and the *links* between each element represent a series of spring-and-dashpot resistant forces. Both the elements and connective forces (links) are initially set in the model, but they are both iteratively varied to produce an earth model with the same seismic response as measured by seismic data collected in the field. Survey objectives and required definition for a particular application dictate the model size and resolution.

Figures 1a through 1h, described in the following paragraphs, illustrate the capability of DEM-PFC type modeling. Sources and receivers can be placed at any position in a model. The model is a 10-foot by 10-foot 2D grid representation. Figure 1a presents the model that includes surface topography, has a resolution of 0.5 feet (i.e., 2 elements per foot), and shows moveout of a seismic wavefront in a homogeneous medium. Arrows indicate wavefront direction from a point source. GAP models use a tight tetrahedral node packing instead of a cubic grid. Figure 1b represents the same model at a resolution of 0.1 feet. The wavefront should be a perfect circle for a model with zero error (very close for initial model). With only a slight modification the model can now simulate a layer of soil overlying a competent bedrock rock interface (Figure 1c). Figure 1d shows a plot of the initial model velocities. The velocities of the elements are only shown for reference. The actual velocities are carried in the links, and allow for anisotropic inversion.



(a) (b)

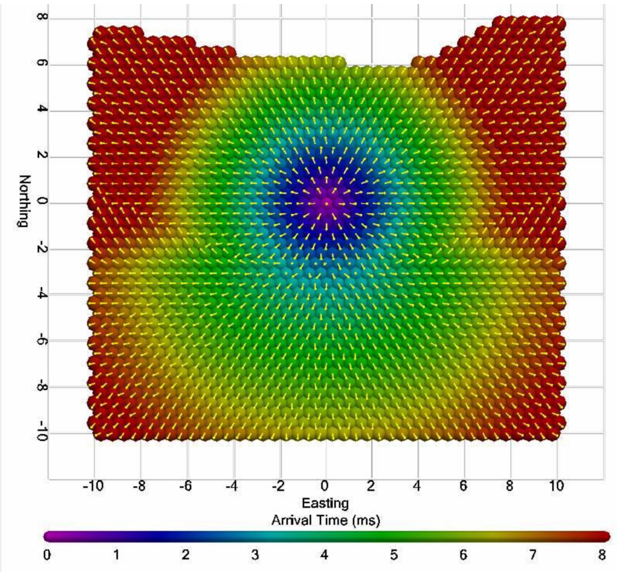
Figures 1a & b. Wavefront arrival times in a homogeneous DEM model with a point source at 0,0; different resolutions (0.5 feet in a. and 0.1 feet in b) represent 2 and 10 elements per foot, respectively.



(c) (d)

Figure 1c & d. Initial earth model with soil overlying rock (c) and initial model velocities (d).

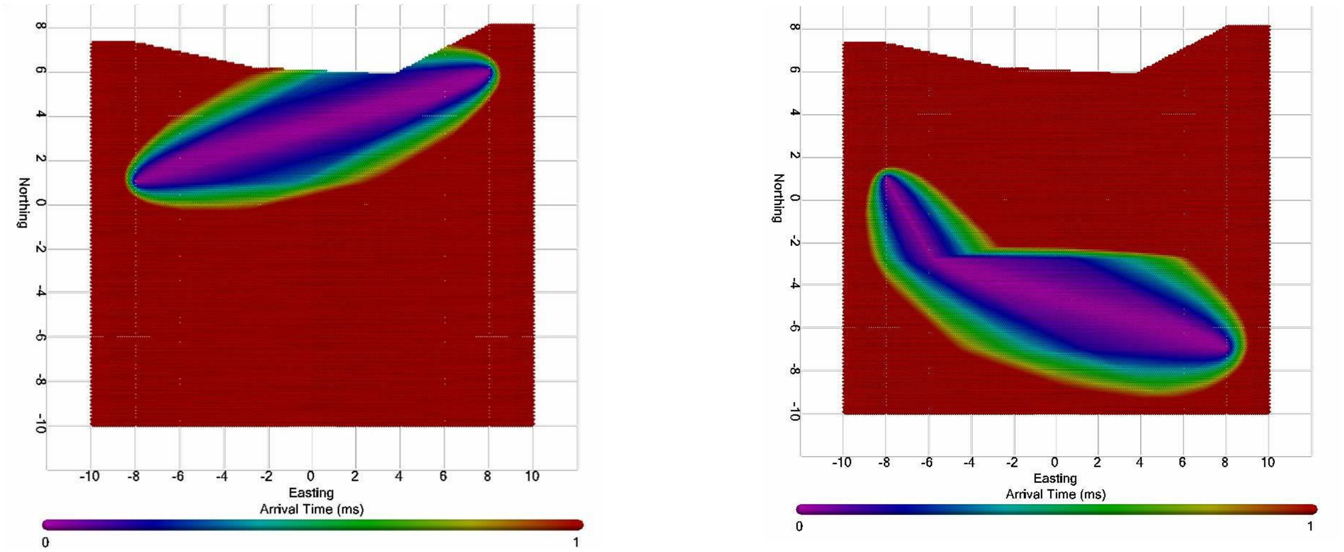
Figure 1e shows moveout of the wavefront for a source originating at grid coordinate 0E,0N in the earth model (easting coordinates given first in GAP model space). As anticipated, the wavefront expands faster in the higher velocity rock. Yellow wavefront direction arrows are shown in the elements, where direct and refracted energy can be observed.



(e)

Figure 1e. Wavefront from a point source moving through the earth model.

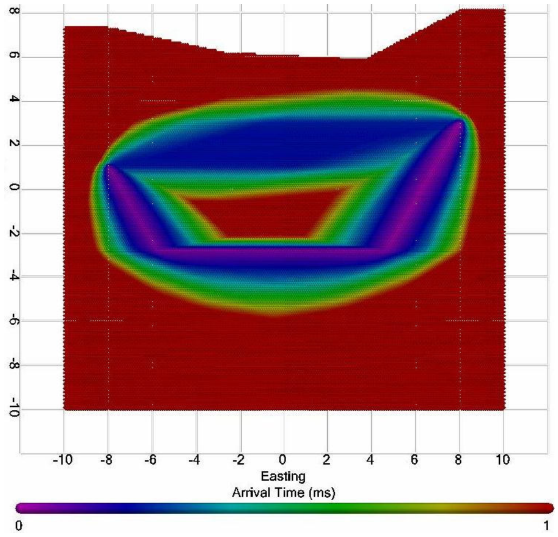
A "*straight ray-path*" simulation with a source at (-8,1) and a single receiver at (8,6) is shown in Figure 1f. Seismic waves do not travel in straight ray-paths through anisotropic earth materials. The elliptical region corresponds to the area most likely to affect measured arrival times, and is used for model inversion,. Figure 1g shows a "*curved ray-path*" with a source at (-8,1) and a receiver at (8,-7). The ray-path area is wider in the higher velocity (rock) portion of the model. Note the sharp bend at the soil/rock interface.



(f) (g)

Figure 1f & g. Straight raypath arrival time models in the soil layer (f), and curved raypath arrival times starting in the soil and propagating across the soil/rock interface (g) – the arrival time scale is normalized to 1.

To illustrate the DEM-PFC capability, Figure 1h presents a "*multiple ray-path*" waveform moveout simulation with a source at (-8,1) and a receiver at (8,3). One region corresponds to part of the wave traveling directly through the soil layer, and the other region corresponds to refracted wave energy propagating through the rock layer.



(h)

Figure 1h. Multiple ray-path wavefront moving through the earth model – the arrival time scale is normalized to 1.

This modeling approach cannot only model forward modeling simulations (as shown in Figures 1a-1h), but also can to produce refraction tomograms from inverse modeling of field data. The procedure is complete with pilot signal correlation (for chirp signals), digital signal filtering, automated first-arrival time picking, and supports borehole deviation surveys, all in either 2D and 3D.

Case Histories

The following two sections present case histories where geophysical testing, using standard 2D seismic refraction field techniques, were conducted for geotechnical investigations. For legal reasons, in both instances, at the client's request site details and project-specific data are not included because (at the time of this publication) they have not yet been released. Both projects are currently active and the geotechnical exploration programs have not been completed. Where geologic and/or geotechnical data are available (and permission granted to present) they are shown, and were incorporated into the GAP modeling.

Condominium Development, Vail, Colorado

In the spring of 2005 geotechnical borings were placed in accessible areas of a proposed multi-level condominium complex located adjacent to a ski slope at Vail, Colorado. The geotechnical exploration program was limited by thick forest vegetation and steep slopes – a black diamond ski slope. In mid-summer Zonge Geosciences began a seismic refraction investigation to supplement the geotechnical data. The objectives were: to map the top of bedrock; determine thickness of overburden soil; and, to evaluate the variability the soil and competency of the bedrock.

The geophysical survey area dimensions were roughly 350 feet north-south and 500 feet east-west. Figure 2 shows a site map, identifying locations of nearby buildings, geotechnical borings, and the seven seismic refraction lines. The area of investigation rises steeply to the south with a slope varying from 20° to 40°. Site geology generally consists of colluvial soils over a weathered bedrock contact, that grades to competent bedrock. Overburden soils predominantly consist of loose, unconsolidated coarse-grained materials (sands, gravels, cobbles and boulders) that range from saturated to unsaturated, depending on the season. The bedrock consists of the sandstones, limestones, and shales of the Minturn Formation. Geotechnical data indicate the soils thickness in the geophysical survey area ranges from 0 feet (i.e., a rock outcrop on the north end of Line 2) to about 50 feet in the southwestern portion of the survey area. Based on blow counts obtained in the soils the relative density varies considerably; and, rock quality also varies dramatically based on core samples and RQD.

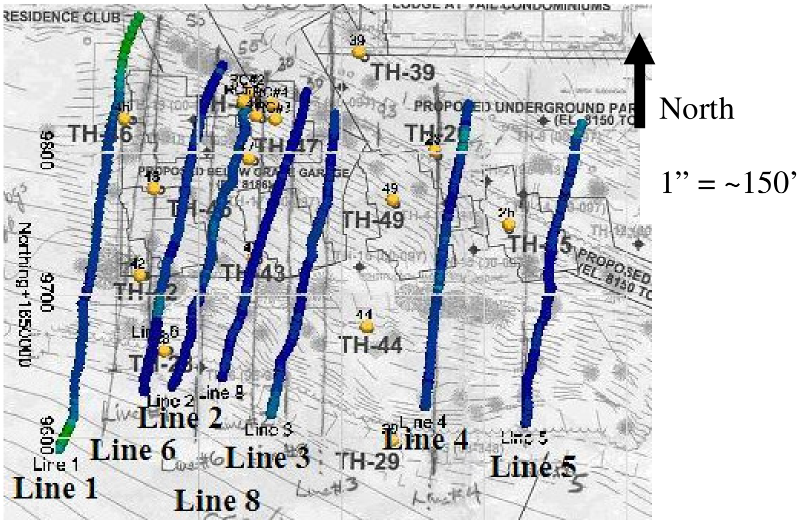


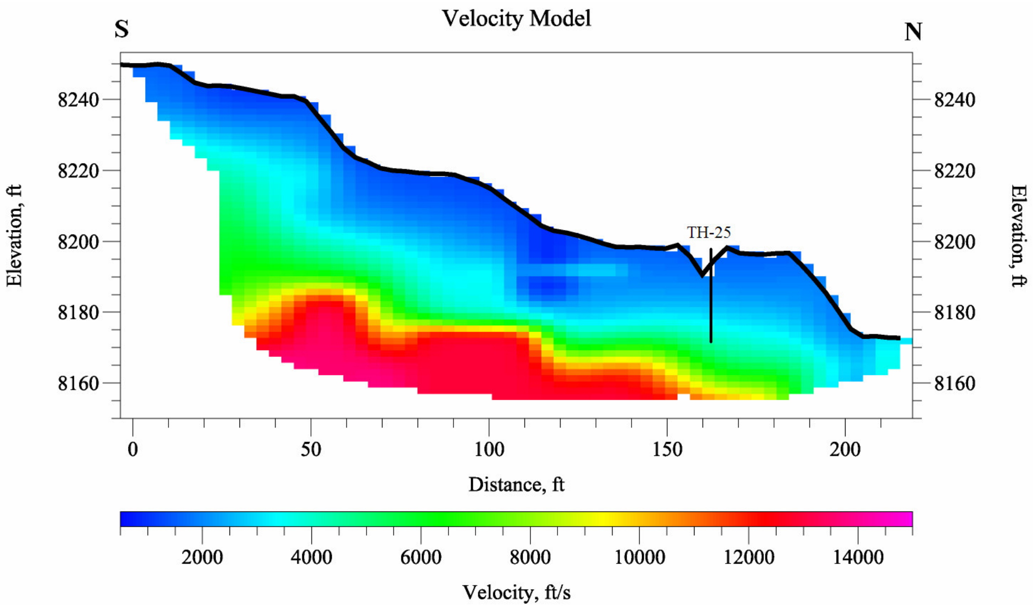
Figure 2. Geophysical survey area showing seismic lines (blue), and geotechnical borehole locations (yellow). The base map shows a proposed layout for six new condo buildings.

GPS coordinates were acquired for most of the geophone and shot locations, however a few positions were interpolated due to poor quality GPS data obtained in the trees. Seismic refraction data were acquired with the following field parameters: a 24-bit seismograph, 24 8-Hz vertical phones, 10 foot receiver spacing (except Line 1 which used 15-foot spacing); hammer and plate source; a minimum of nine shot points per line; 0.25 millisecond sample rate SEG2 records; and a 500 msec record length.

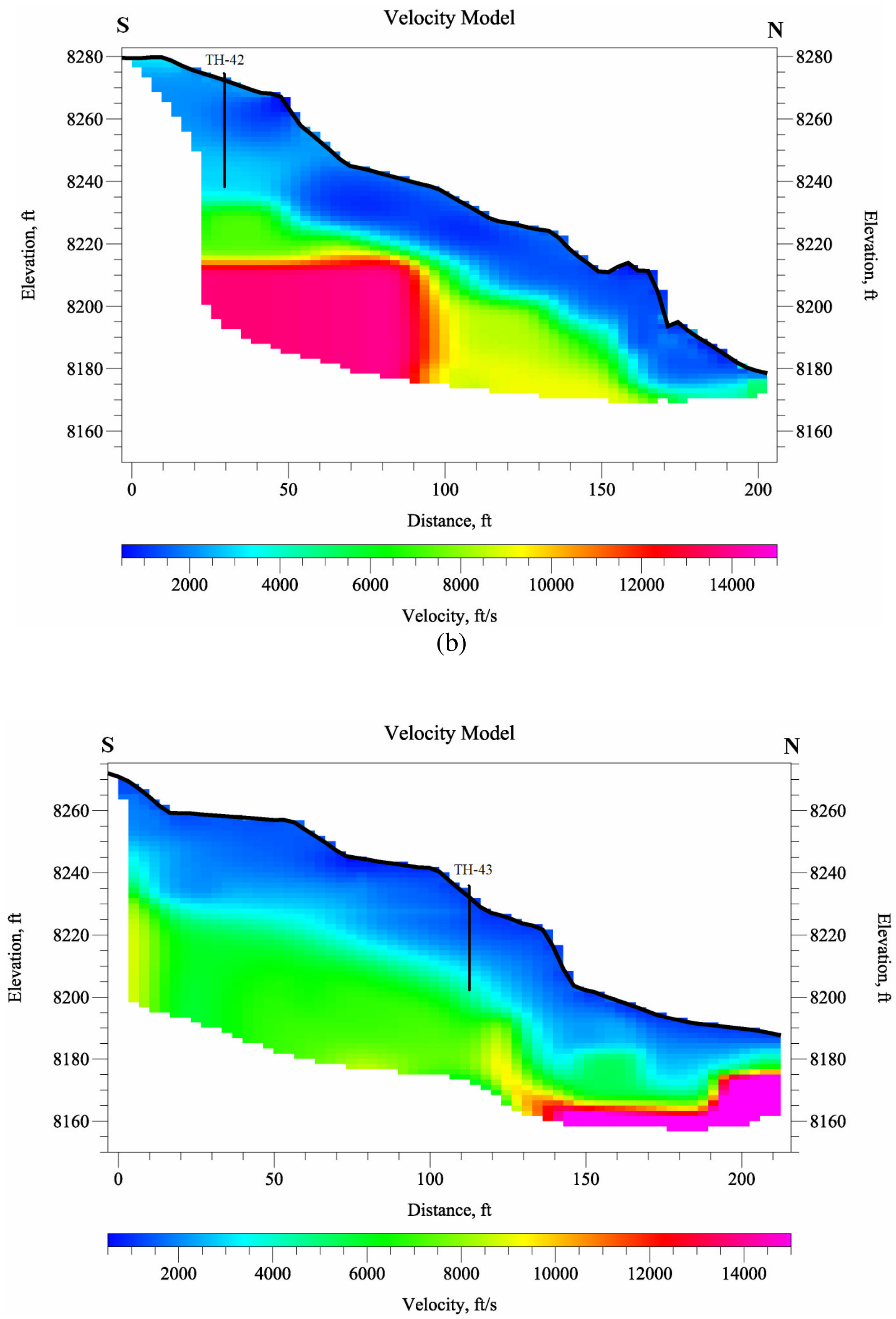
The 2D GAP refraction data processing package had not been fully completed to analyze the data from this project. Therefore, initially data processing involved tomographic inversion using a synthetic annealing algorithm developed by Pullammanappallil and Louie (1994). Tomographic analysis was performed using SeisOpt@2D™, a commercially available 2D refraction tomography imaging package (Optim, 2005).

All seven lines were processed with the same parameters in SeisOpt@2D, and results from 3 lines are presented here. Tomograms from Lines 5, 6, and 8 are presented in Figures 3a, b and c, respectively. The 2D images show the velocity distribution below the refraction line. Interpretation of the P-wave velocities obtained indicate: 1) low-velocity materials interpreted as the overburden colluvial soils (shaded in blues / cool colors); 2) moderate-velocity materials interpreted as weathered bedrock (shaded in greens); and, 3) high-velocity materials interpreted as competent bedrock (shown in yellow and red / hot colors). Data quality was very good for all lines and showed consistent interpretations.

Borehole information, including elevation for top of bedrock, was provided by the geotechnical engineers. These borehole data (labeled TH for test holes in Figures 3a-c) were projected onto the nearest velocity line. Test hole projection was done '*along the elevation contour*', as recommended by the geotechnical engineer. By mathematically comparing the top of bedrock encountered in all the borings to the velocity data produced with tomography, it was determined that the breakover from overburden soil to bedrock occurs at an *average* P-wave velocity of 6,300 feet/second (light green). There is a gradational boundary between the overburden and bedrock, probably caused by variable degree of weathering on the bedrock interface, as documented in the test hole logs. Competent bedrock was detected beneath each line (yellow-red). Although, the depth to- and the amount of- hard bedrock appears to be quite variable between each of the seven lines. This layer interpreted as competent limestone bedrock was not encountered during test hole drilling.



(a)



(b)

(c)

Figure 3. 2D Refraction tomograms for Line 5 (a), Line 6 (b), and Line 8 (c). TH represents nearest geotechnical boring and the line represents the soil thickness as measured in the TH (i.e., top of rock).

Advanced 3D modeling was requested by the client to gain a greater understand the irregular bedrock surface for design, excavation, and construction of the condominiums. With the 2D velocity tomography results, and good borehole control a calibrated GAP 3D velocity model could be constructed for the survey area. Contoured isosurfaces were generated with both the velocity and the borehole data using a B-spline interpolation with non-symmetric linear Voronoi Basis functions. This technique was used for all the elevation data and for combining the 2D velocity profiles with the geotechnical borehole information to provide a calibrated 3D model. Each individual velocity profile (as shown in Figure 3) was used to assess competency of the rock. However by calibrating the velocities using borehole data, the GAP models provided: "3D soil thickness (isopach)" (Figure 4); and "3D top of weathered bedrock" (Figure 5) as well as "3D top of competent bedrock" (Figure 6) isosurfaces. These 3D models show only one perspective view (generally looking south towards the mountain). Of course the 3D model can be rotated for any perspective, and different velocity slicing produces unique isosurfaces. The 3D model will be used to evaluate the thickness of the overburden soil deposits, the relief of the weathered bedrock and the extent of competent bedrock and how it affects foundation design and construction of a 5-story underground garage. Figure 7 shows a plan (2D) depth to bedrock map produced through the GAP DEM-PFC analysis which incorporated the geotechnical borehole and the geophysical seismic data.

The seismic data for this project were acquired in 2D. The mathematical interpolation between lines created 2.5D images of the subsurface, but the models shown in Figures 4, 5 and 6, are not just images. The represent a 'snap shot' of the GAP model that will be used for the next phase of work – design and construction of structures. This is the value added, or the advancement that DEM-PFC modeling of seismic data brings our industry. Whether the GAP data are presented in 2D, 2.5D or 3D they are calibrated models, not images, to be used by the engineers.

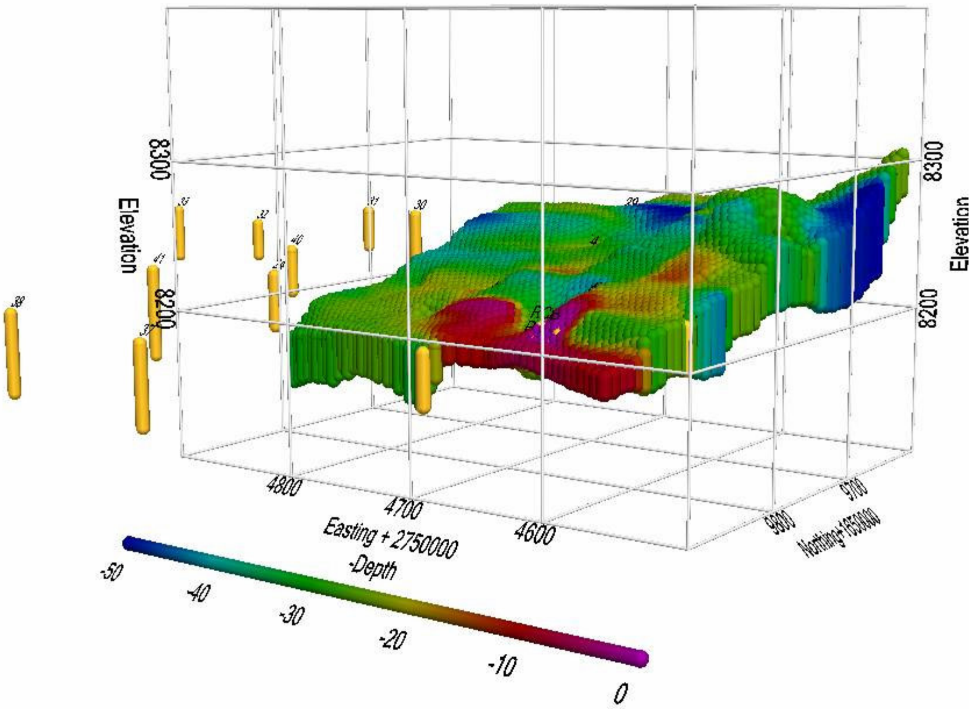


Figure 4. 3D model isopach of soil overburden (units in feet) - perspective view to the southeast. Yellow 'bars' are the location (and number) of geotechnical borings, where the length represents depth to weathered bedrock.

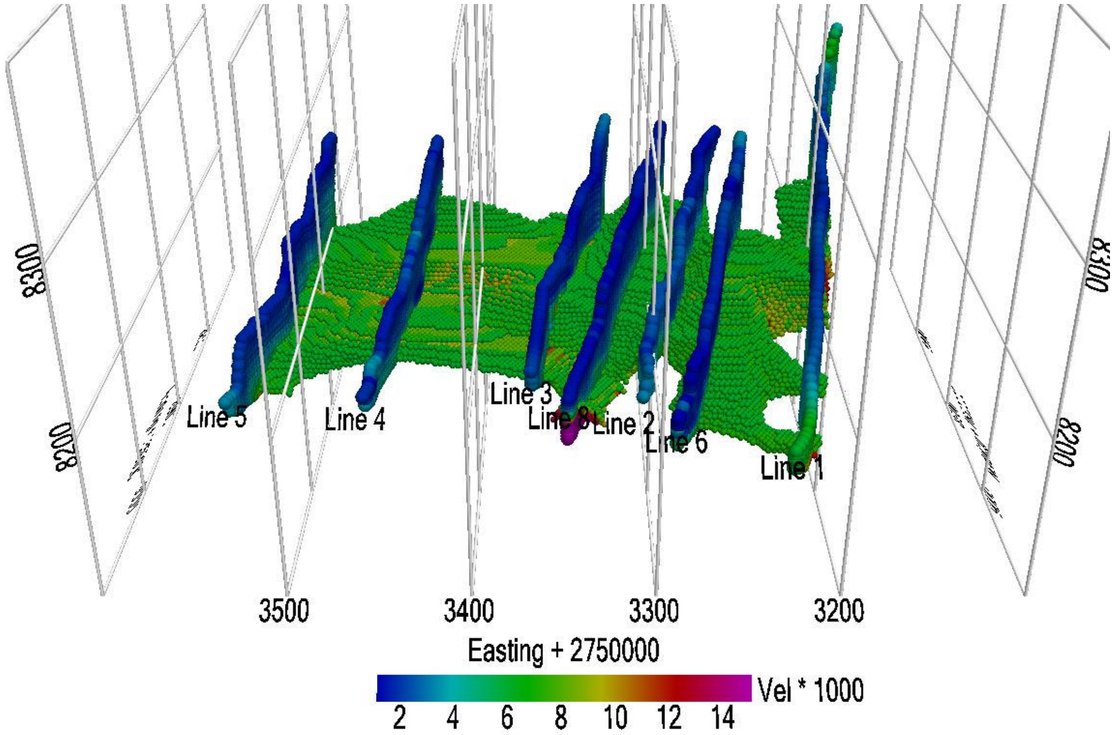


Figure 5. 3D model top of *weathered* bedrock based on a velocity isosurface (slice) at 6,300 ft/sec (units in feet & ft/sec) - perspective view to the south. Top of the refraction lines is the ground surface.

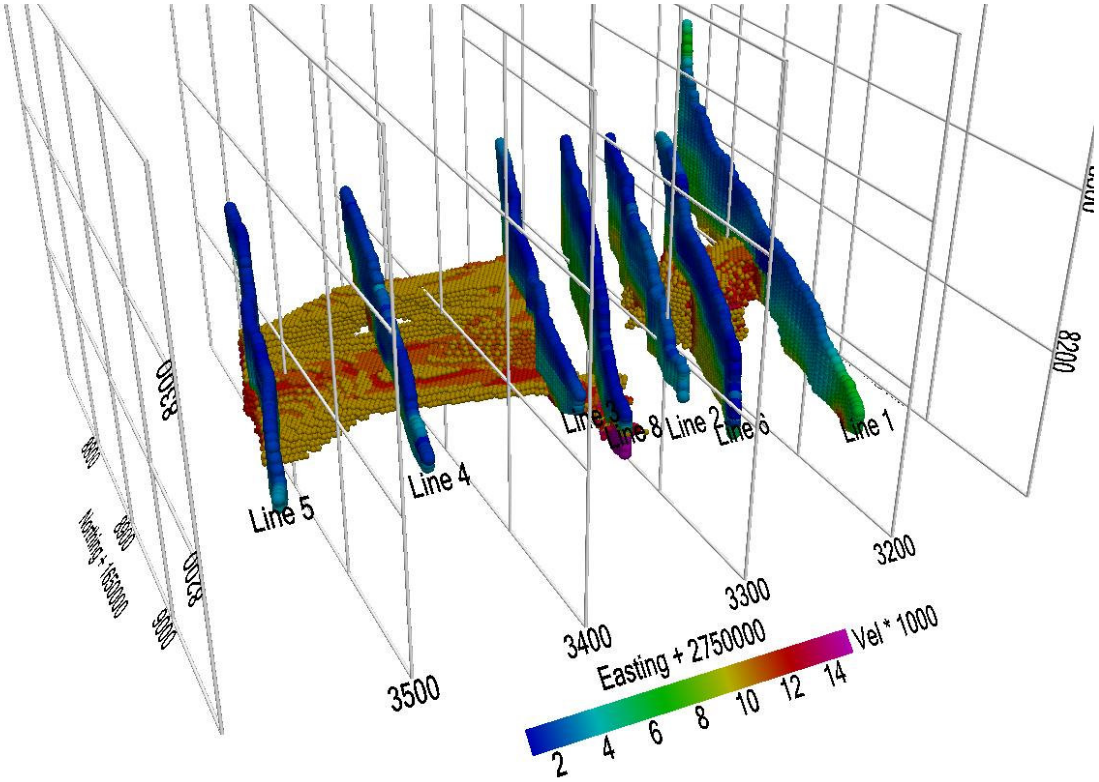


Figure 6. 3D top of competent bedrock based on a velocity isosurface of 11,000 ft/sec (units in feet & ft/sec) - perspective view to the southwest.

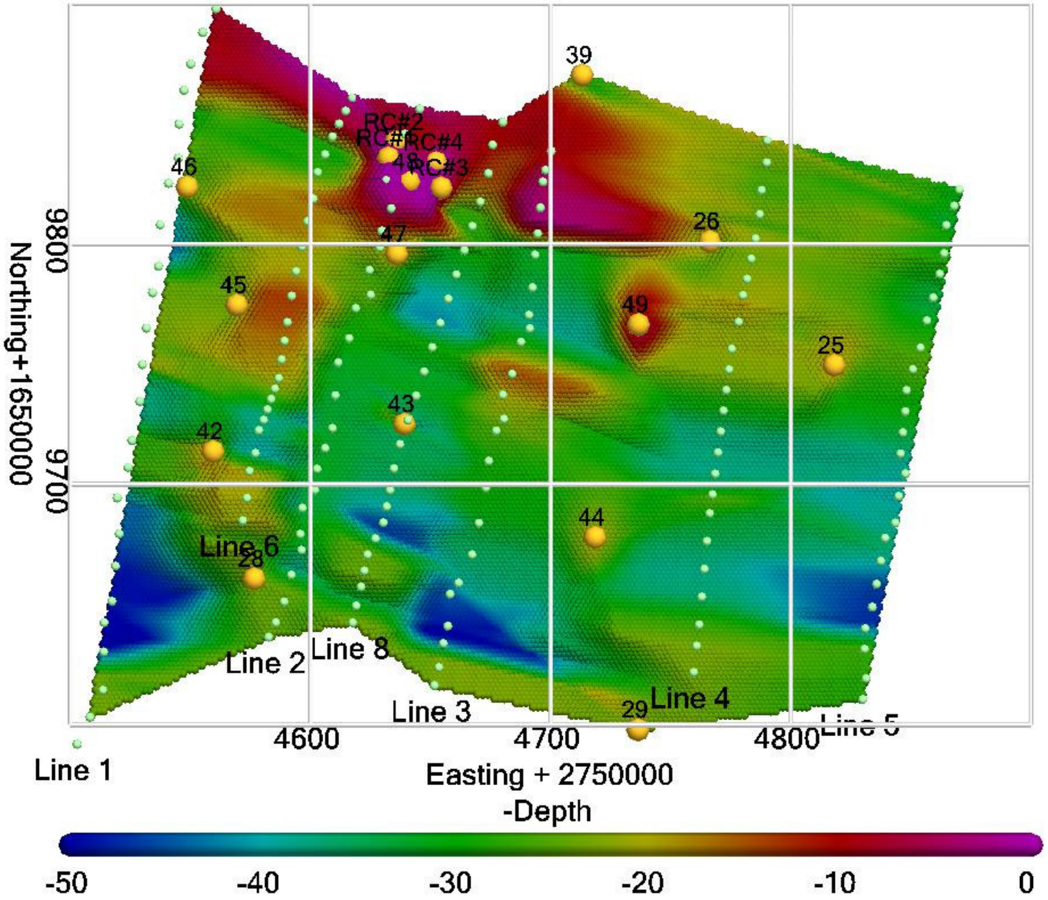


Figure 7. 2D plan map of depth to bedrock - green dots are geophone positions and yellow dots are borehole positions with TH number. Note zero thickness at the rock outcrop (RC) at north end of Line 2 which is the base of the hill. All units in feet, north is to the top.

Blue Ridge Landslide, Sterling, North Carolina

Modeling of 2D seismic refraction data was performed for the Eastern Federal Lands Highway Division (EFLHD) of the Federal Highway Administration. The geophysical survey consisted of investigating a landslide that is currently active; as such, details regarding the geotechnical analysis cannot be provided. The model results were provided by EFLHD personnel, as analyzed using the GAP processing approach. Seismic data were acquired by EFLHD staff and processed by Summit Peak Technologies. The following is a brief description of the project provided by EFLHD, and example 3D seismic plots.

Based on review of highway plans and previous geotechnical investigations, the landslide is through a large hillside of soil. This is a natural landslide area consisting of colluvial soil (landslide debris) deposits, overlying residual soils, and ultimately bedrock at depth. The colluvium consists of boulders with sand and silt and the residual soils consist of micaceous silty sands and sandy silts formed by in-place weathering of the parent mica gneiss and schist bedrock. At this point, it is not certain what caused a reactivation of movement, however, it is believed the slide may be occurring at the interface between colluvial deposits and residual soils and is exaggerated by a rise in the static water table (*personal communication with Khalid Mohamed geotechnical engineer at EFLHD*).

An GAP model space was generated based on the survey coordinate data provided from EFLHD. Data were acquired along 4 lines, using 12-channels with geophones spaced 10-feet apart and 11 shots per line. A hammer and plate were used as the source. Signals were combined for the common-shot and common-receiver positions, and are analyzed beneath the corresponding locations. Figure 8 shows the common-shot record for Survey Line 1, shot position S-5. The signals are all plotted and clipped at the same amplitude levels. Arrival-times were then picked for each SEG2 shot record using an auto-picker (a module in the processing package) then authenticated manually. The manual picks were used to train the automatic picker. The automated picker discarded signals with low confidence picks. All arrival-time picks were cross-examined in both common-shot and common-receiver plots.

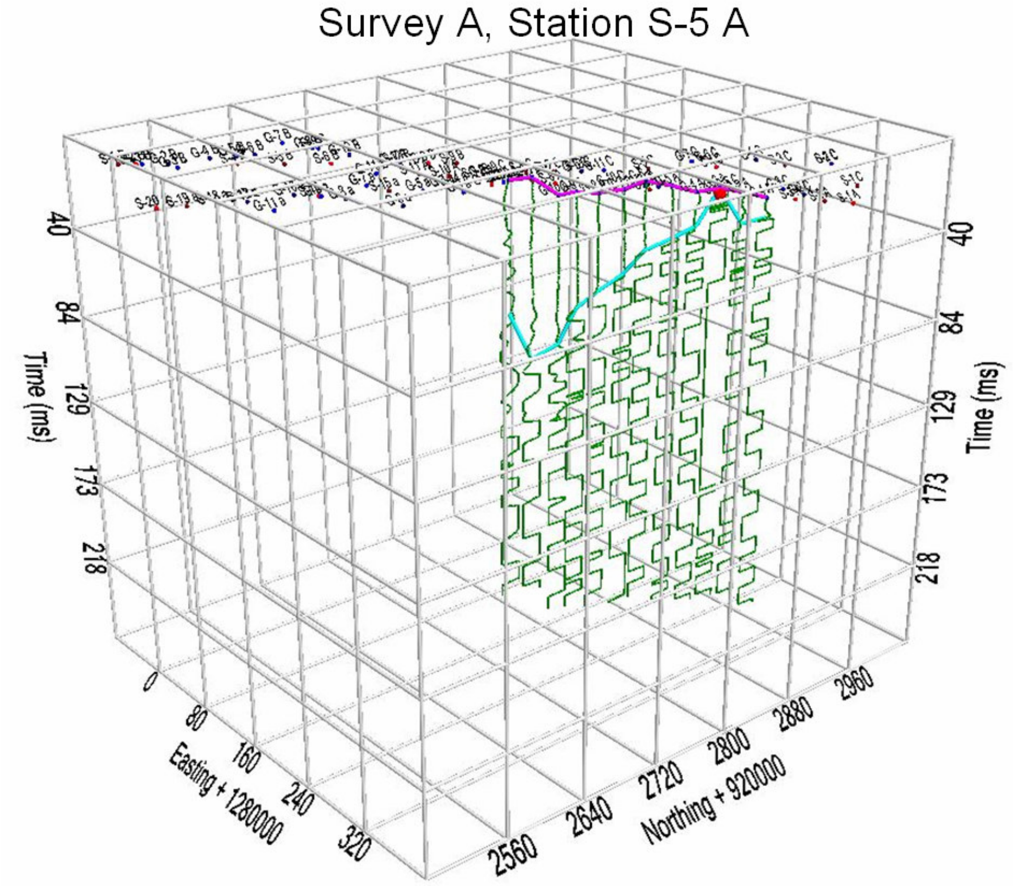


Figure 8. Common shot signals with picks (shown in light blue).

Two iterations were computed at 32-, 16-, 8-, and 4-foot resolutions. This technique allows 2D tomographic reconstruction at higher resolution with reduced distortion. The resulting 3D velocity model, obtained by using borehole (1D) and velocity (2D) images is shown in Figure 9. The 2D refraction tomogram in Figure 9 was computed in 8 iterations using GAP starting from a homogenous velocity model.

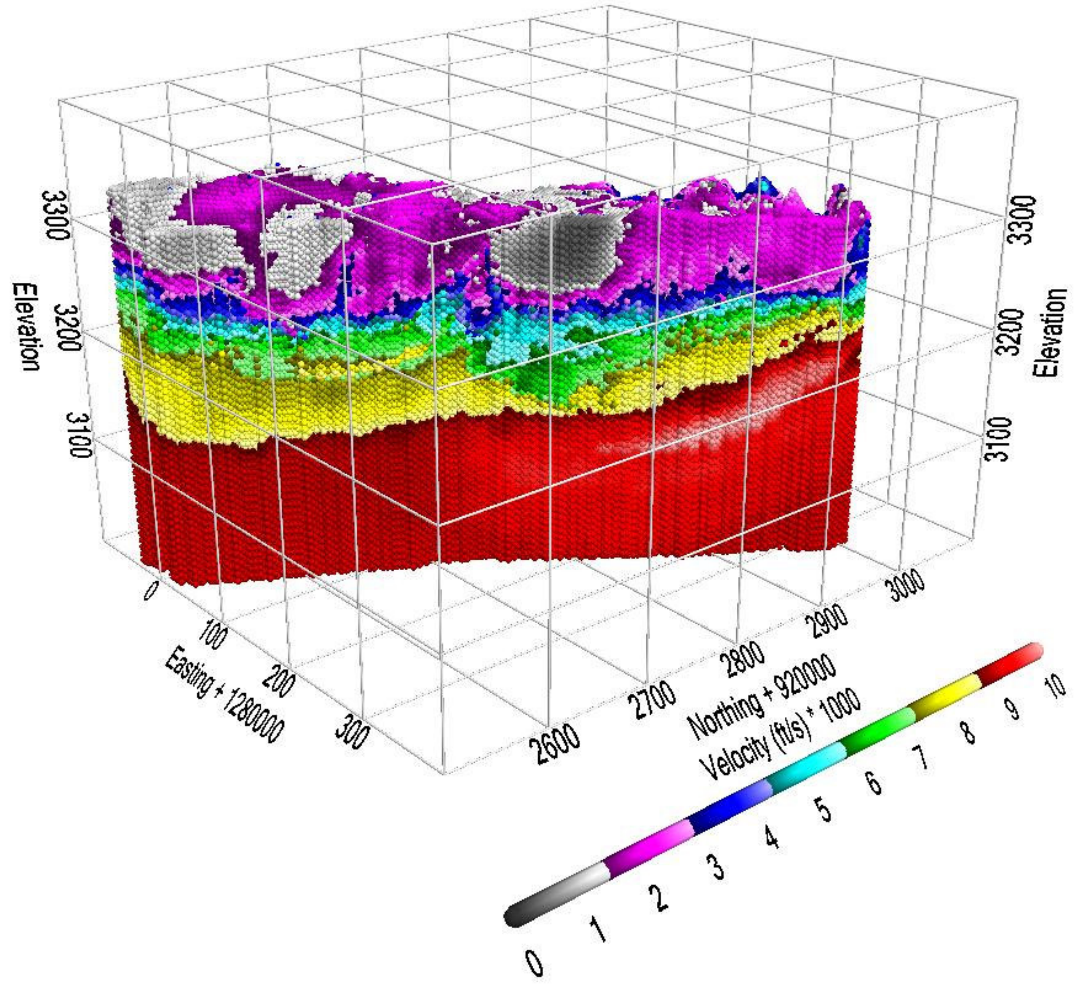


Figure 9. Refraction tomography velocity model using 4-foot resolution.

Using boring logs from the geotechnical investigation seismic velocities were mapped to match geologic materials. The resultant 3D model, presented in Figure 10, identifies the material types and their distribution in the model, as defined by seismic velocities. An advantage of using refraction tomography reconstruction is that it has much better capability of mapping both vertical and lateral velocity variations. An GAP 3D plot of the velocity variation *within* each geologic layer is shown in Figure 11.

The ray-path coverage for all rays in the model is shown in Figure 12. A ray is a region in the model that has the highest contribution to the first arrival time, and typically descends from the source at the ground surface to higher velocity layers before ascending to the surface receiver(s). From the ray-path coverage model, it is clear that the rays descended approximately 150 feet below the surface. Velocity data shown below this depth (in Figures 9, 10, or 11) are not constrained by the model parameters, as first-arrival seismic energy was not transmitted through these deeper portions of the DEM-PFC model.

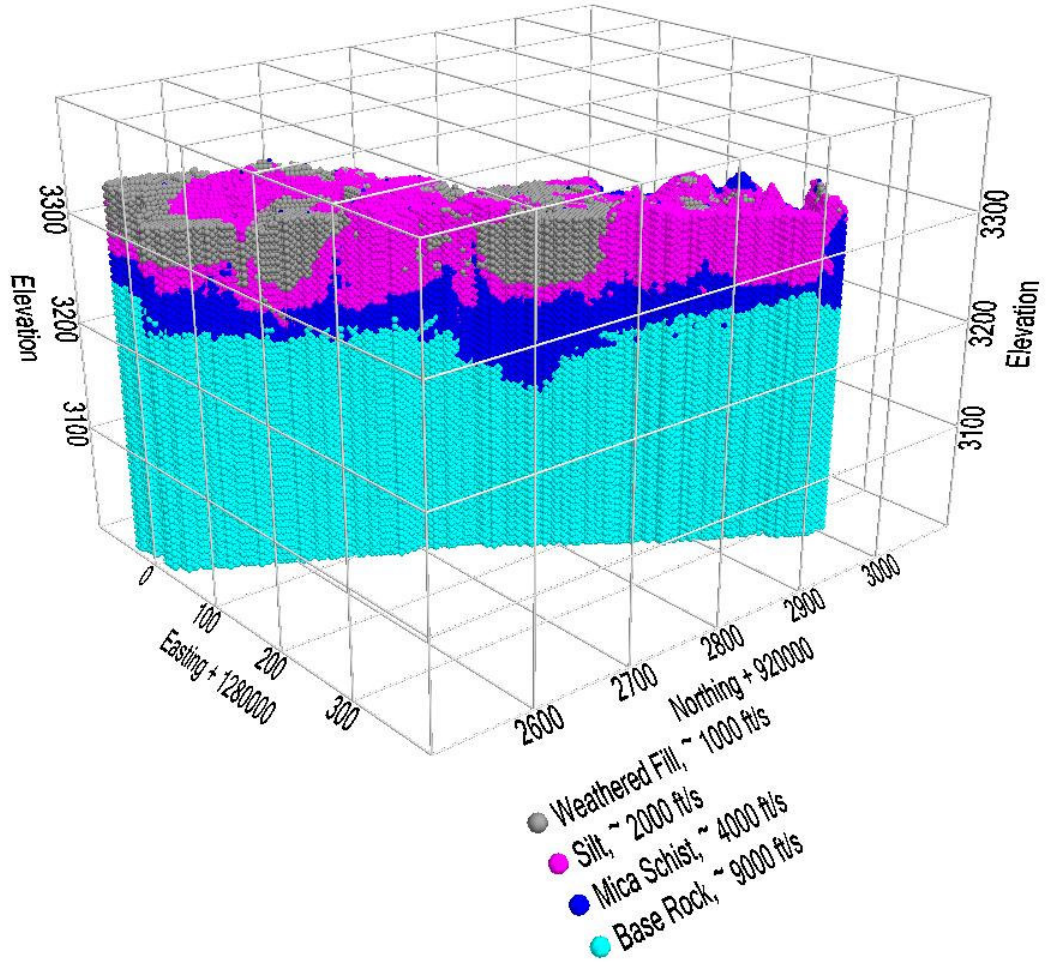


Figure 10. Refraction tomography *material* model as derived from geologic boring logs.

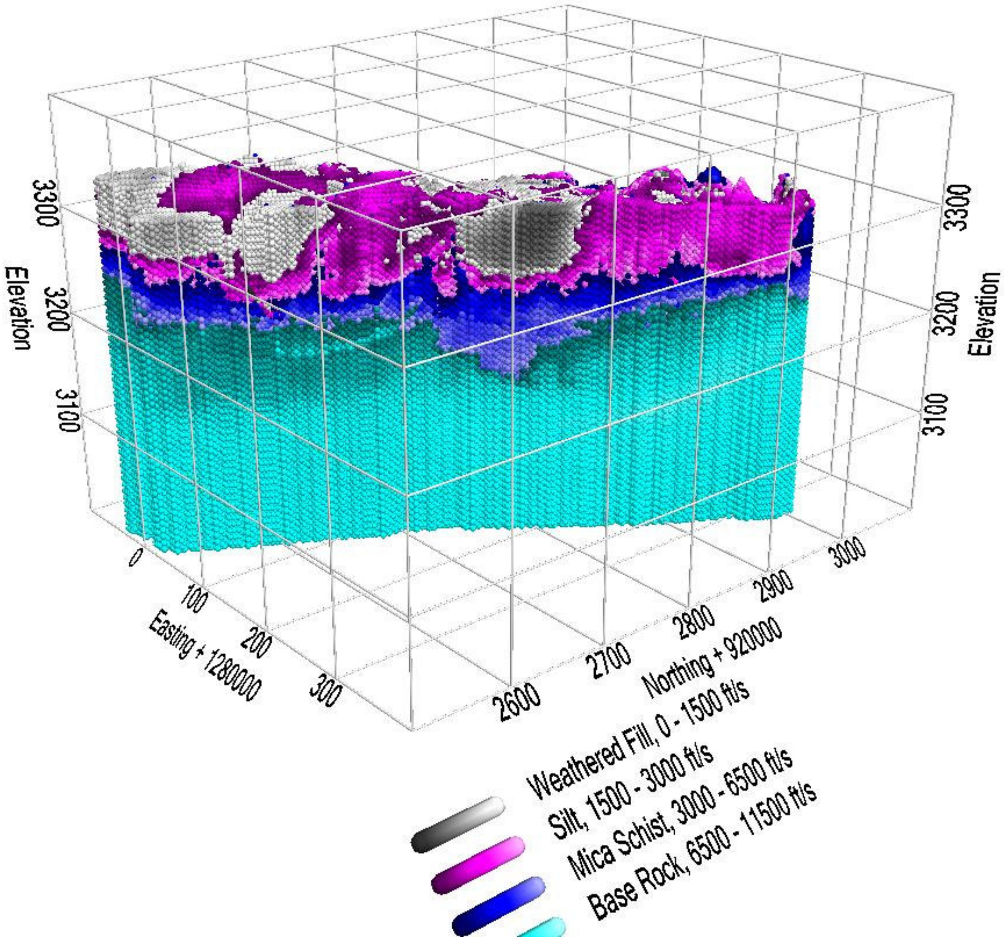


Figure 11. Refraction tomography model showing the velocity variation within each of the material layers (color scales shown in legend).

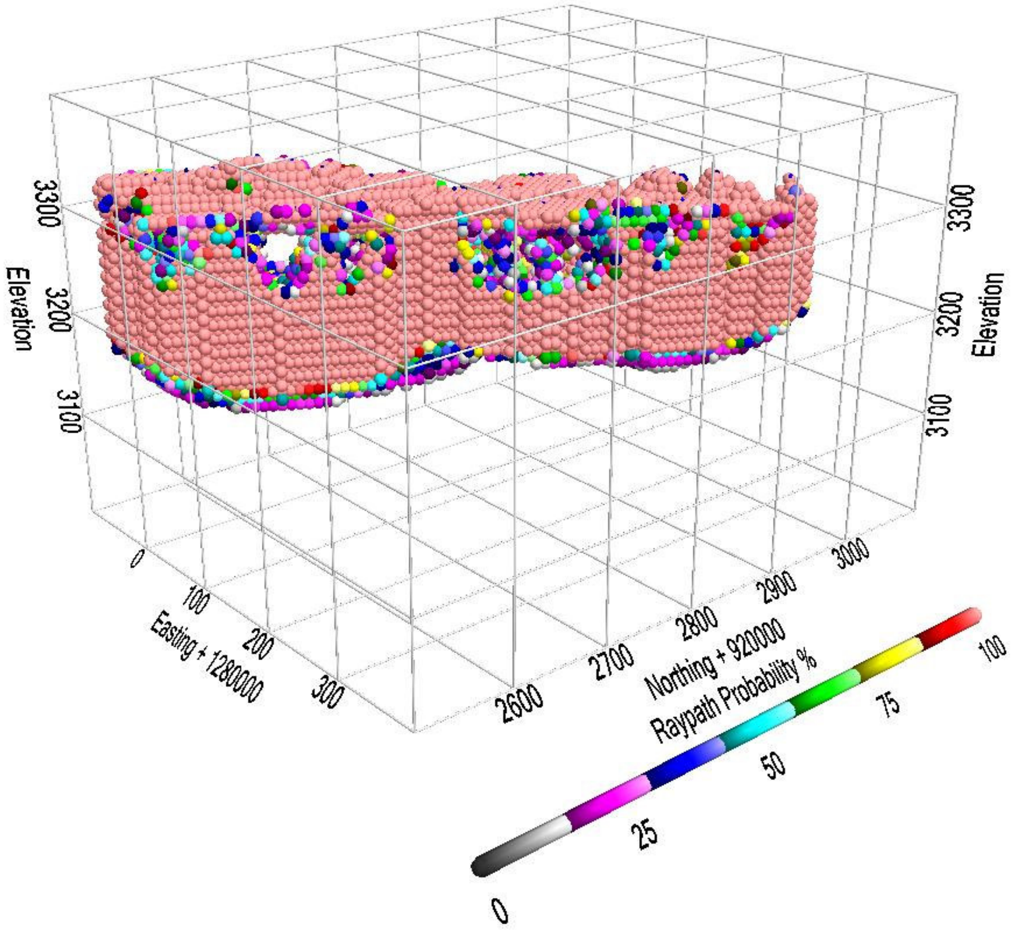


Figure 12. 3D model of ray coverage using probability (%).

Conclusions

Applying a more comprehensive numerical modeling approach to process and present seismic refraction data using the Geostructural Analysis Package (GAP) is described in this paper. GAP is a robust discrete element particle flow modeling technique that can produce high-resolution 2D and 3D models through forward modeling (simulations) as well as inverse modeling of standard seismic refraction data. The models are generated such that seismic wave arrival times simulated in the model match arrival times measured in the field. The same technique is used to modify the material properties in the model to reduce differences between the model waveforms and the field waveforms.

The name refraction tomography may perhaps be misleading for what GAP performs. GAP is optimized for seismic wave propagation, as shown here, but its purpose is much broader in scope to model chemical, thermodynamic, and hydrologic processes as well. In its current form it supports tomographic and holographic inversion. The algorithm includes a wide range of built-in signal processing capabilities, such as automatic arrival time picking and digital filtering. It can efficiently image low velocity regions in the subsurface because it increases resolution with each iteration and reduces arrival time errors using Fresnel volumes, or curved ray-path regions. The GAP technique of matching arrival times will be extended to match the full waveforms, and will then be termed *surface holography inversion*.

This modeling approach is gaining acceptance within the engineering community because of its added value to produce a 2D or 3D model. Two case histories with complex geologic settings and site conditions show the value of integrating geological and geotechnical data into the GAP modeling process. Each case history used standard 2D refraction field procedures, data were processed using 2D tomography inversion, then calibrated 3D models were generated through interpolation. The models could be considered 2.5D based on the procedures used, but the model is 3D. These volume models can be velocity sliced to strip away materials, or geologic layers, calibrated to have a particular velocity or range of velocities.

Perhaps the most important advancement using discrete element particle flow code is the models can be used in the next step of engineering analyses. As refraction data can be acquired in 3D, and field appropriate field parameters are used, GAP can support full 3D processing of these data to produce calibrated models which incorporate geologic, geotechnical, and geophysical data. After the geophysics is done, the models can then be used for engineering analyses. For example, they can undergo large-strain deformation such as cracking, subsidence, or slope failure modes; and, low-strain static and dynamic loading. Clearly, this is an advantage over producing 2D, 2.5D or 3D images of the subsurface for geotechnical applications. As the capabilities increase for GAP to model other processes such as chemical, thermodynamics of heat flow, or groundwater flow it will become a very powerful and useful tool for applications other than geotechnical engineering.

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