Advancements in 3D Subsurface Modeling Using Seismic Refraction Data – *A New Perspective*

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ABSTRACT

Standard subsurface imaging using seismic refraction data produces two-dimensional (2D) images of the subsurface. Engineers and geologists (i.e., the end users) typically must integrate other subsurface data with results from a seismic investigation. Advancements in refraction data analysis have increased the ability to image geologic features and provide better 2D graphical presentation of refraction results. As refraction tomography increases the ability to meet project objectives and present 2D color images more representative of the subsurface, we begin to approach the end users needs. That is, the end product from a refraction survey can be either a 2D image or a full 3D model. Full 3D earth models can be used for many purposes after the geophysical survey is complete. Subsurface physical property data in 3D model space permits assessment of a site from a whole new perspective. For example: structural loading, seismic loading, or construction excavation requirements can be uniquely handled using 3D model results.

This paper presents an advanced approach to refraction data processing, presentation, and visualization, using the "*Geostructural Analysis Package*" (GAP). GAP incorporates several numerical modeling processes: discrete element method, particle flow code, finite differencing, and the material point method. These four numerical modeling methods have been combined and optimized for seismic applications. GAP is an innovative tool that allows better data analysis and presentation that can be used to produce 3D volumetric models for further analysis. For example, mapping top-of-rock may be the objective of a geophysical investigation, but it is not the engineering purpose of the survey (e.g., construction of critical structures – a dam or a bridge foundation).

3D model results from two case histories are presented to demonstrate the benefit of processing and presenting seismic refraction data using a new perspective – GAP modeling. GAP represents the newest advancement in subsurface modeling using refraction data.

KEY WORDS: seismic, refraction, tomography, 3D modeling

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 two dimensional (2D) images of the subsurface. It has been effective, proven, and valuable as a method to analyze refraction data. Similarly, over the past decade multiple refraction tomography algorithms have been developed as the next generation of tools for data analysis, presentation and visualization of refraction data. These newer, more complex mathematical approaches, generally termed tomography, vary to some degree in their approach, but the image results are generally comparable (Sheehan, 2005). In either case, using GRM or tomography analyses produces 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 produce 2D models.

The purpose of this paper is to introduce a new approach to analyze seismic refraction data. Like all geophysical data analysis methods GRM, refraction tomography, and 2D finite difference models each have their value, strengths, and weaknesses. 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 necessary.

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 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 GAP 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. GAP 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, which has been 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.

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, determining 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.

CASE HISTORIES

The following brief case histories are geophysical investigations using standard 2D seismic refraction field techniques conducted for geotechnical investigations. For legal reasons and at the client's request project-specific data are not included because final results from the two projects have not yet been released. Permission was granted to include the geologic, geophysical, and geotechnical data presented in this paper.

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 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 1 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. Bedrock consists of the sandstone, limestone, and shale 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.

GPS coordinates were acquired for most of the geophone and shot positions, however a few of them had to be interpolated due to poor quality GPS coverage 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.
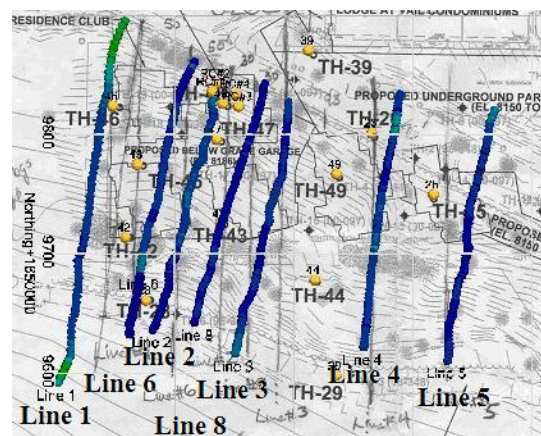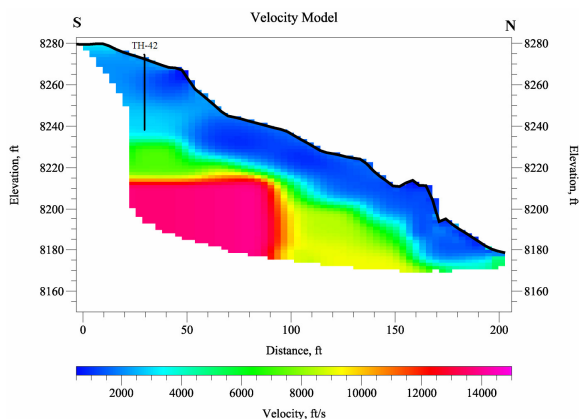

Figure 1. Refraction survey line layout.

The GAP refraction data processing package had not been fully completed to analyze the 2D data from this project. Hence, initial 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. An example tomogram from Line 6 is presented in Figures 2. The 2D image shows 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 (shades of green); 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 in 11 borings was provided by the geotechnical engineers. These borehole data (e.g., boring shown with a "TH" for test holes on Figures 1 and 2) were projected onto the nearest velocity line. Test hole projection was done along the elevation contour, as recommended by the engineer. By mathematically comparing the top of bedrock encountered in all the borings to the velocity data produced with tomography, it was calculated that the break over 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. Although, the depth to- and the amount of- hard bedrock appears to be quite variable between each of the seven lines.

Advanced 3D modeling was requested by the client to gain a greater understand the irregular bedrock surface (defined by the borehole and seismic investigations) for

Figure 2. 2D Refraction tomogram for Line 6.

Figure 3. 3D isopach of soil thickness (units in feet). Yellow bars show the position of geotechnical borings, and the length represents depth to bedrock.

Figure 4. 3D GAP model top of weathered bedrock surface based on a velocity isosurface at 6,300 ft/sec (units in feet & ft/sec).

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 (e.g., Figure 2) was used to assess competency and variability of the bedrock. However by calibrating the velocities using borehole data, the modeling provided soil thickness (i.e., isopach) as shown in Figure 3, and top of weathered bedrock (Figure 4). These GAP model results only show a perspective view, generally looking south towards the mountain-side. The 3D model can be rotated for any perspective view, and different velocity slicing produces unique isosurfaces. The seismic data were used to evaluate foundation design and construction of a 5-story underground garage. Initial feedback from the client during the 2006 construction season indicates the seismic imaging *"was very accurate and well worth the price"* (Koechlein Engineering Consultants, *personal communication)*.

Seismic refraction data for this project were acquired in 2D. The mathematical interpolation between lines created 2.5D images of the subsurface, but the data shown in the models (Figures 3 and 4), are not just images. They represent snap shots of the modeling that were used during the next phase of engineering 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 geologists and engineers.
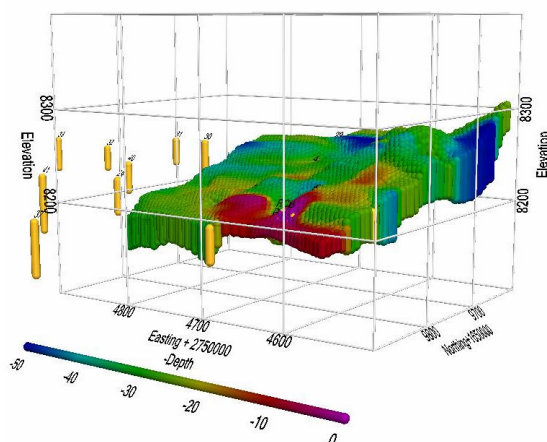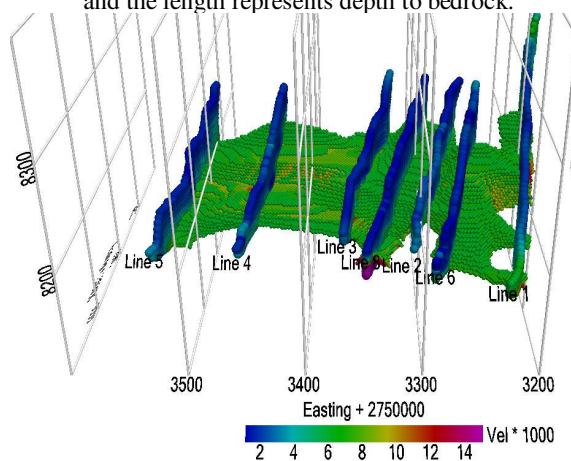
**Blue Ridge Landslide, Sterling, North Carolina**
Modeling of 2D seismic refraction data was performed for the Eastern Federal Lands Highway Division (EFLHD) of the Federal Highway Administration. The geophysical survey consisted of investigating a landslide that is currently active; as such, details 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*).

The 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. Arrival-times were then picked for each shot record using an auto-picker (a module in the GAP 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.

Two tomography iterations were computed in GAP at 32-, 16-, 8-, and 4-foot resolutions. This technique allows 2D 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 5. The 3D velocity model in Figure 5 was computed in 8 iterations using GAP starting from a homogenous high-velocity model.
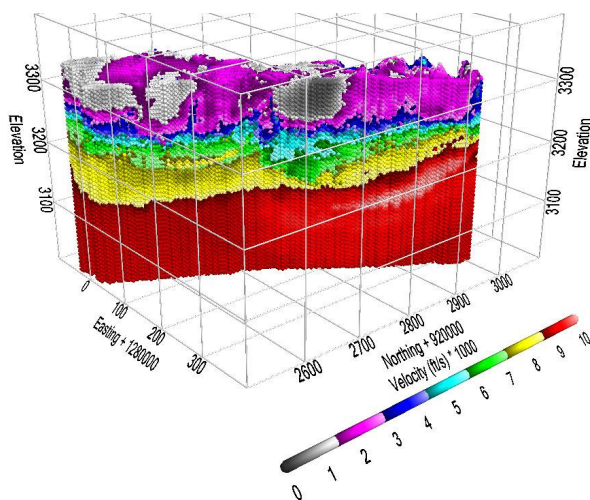

Figure 5. 3D refraction tomography velocity model (4-foot DEM resolution).

Using boring logs from the geotechnical investigation seismic velocities were next mapped to match geologic materials. The resultant 3D *lithology model*, presented in Figure 6, 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. A GAP 3D plot of the velocity variation *within* each lithology is shown in Figure 7.
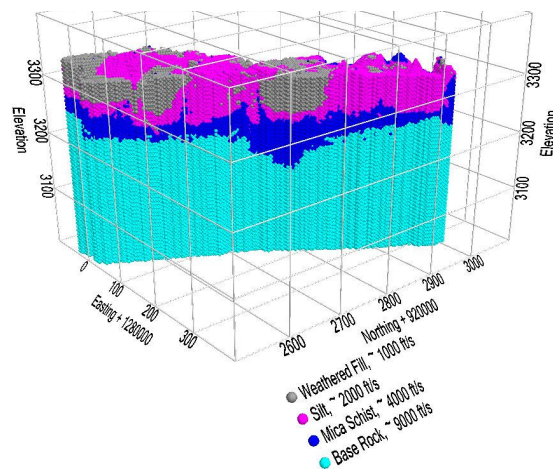
Figure 6. 3D refraction *lithology model* (derived from correlation of geologic with tomography velocities).
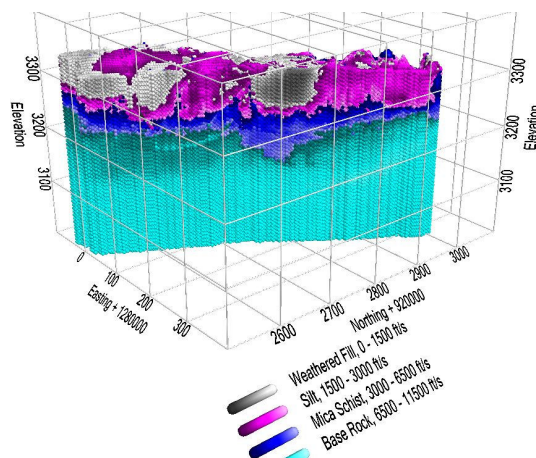
Figure 7. 3D refraction model showing the velocity variation within each lithology.

Ray-path coverage for all rays in the GAP models is calculated as a probability of its effect to the velocity calculation. From the ray-path coverage model computed at this site it was clear that the rays descended approximately 150 feet below the surface. Therefore, velocity data shown below this depth (in Figures 5, 6, and 7) are not constrained by the model parameters, as first-arrival seismic energy was not transmitted through these deeper portions of the DEM-PFC model.

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, and 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.

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 completed, 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. As the capabilities increase for this code to model other processes such as chemical, thermodynamics of heat flow, or groundwater flow, it will become a powerful and useful tool for applications other than geotechnical engineering.

ACKNOWLEDGEMENTS

REFERENCES
Gelis, C., D. Leparoux, J. Virieux, A. Bitri, S. Operto, and G. Grandjean, 2005, Numerical modeling of surface waves over shallow cavities, Jour. Of Environmental & Engineering Geophysics, Vol. 20, No. 2, pp. 111-121.

Itasca Consulting Group, 1999, PFC2D *Users' Guide*, Command Reference, FISH Reference, and Theory and Background, Minneapolis.

Itasca Consulting Group, Inc., 2003, PFC3D (Particle Flow Code in 3 Dimensions), Ver. 3.0. 656 pp.

Optim, 2005 (SeisOpt@2d Ver. 4.0), Seismic Refraction Tomography software, *copyright* Optim, Inc., University of Nevada, Reno, Nevada.

Palmer, D., 1981, An introduction to the generalized reciprocal method of seismic refraction interpretation, Geophysics, Vol. 46, pp. 1508-1518.

Pullammanappallil, S., J.N. Louie, 1994, A generalized simulated-annealing optimization for inversion of first-arrival times, BSSA, Vol. 84, pp. 1397-1409.

Rock A. and R. Zhang, 2002, Acoustic model calibration, *in* Proceedings of the American Society for Composites 17th Technical Conference.

Rock, A., D. Wilkinson, and R. Zhang, 2005, Velocity variations in Drilled Shaft CSL Surveys, Report to Federal Highway Administration, Publication No. FHWA-CFL/TD-04-001.

Saenger, E.H., Gold, N., and Shapiro, S.A., 2000, Modeling the propagation of elastic waves using a modified finite difference grid: Wave Motion, Vol. 31, pp. 77-92.

Saenger, E.H., and Bohlen, T., 2004, Finite Difference Modeling of viscoelastic and anisotropic wave propagation using the rotated grid: Geophysics, Vol. 69, No. 2, pp. 583-591.

Sheehan, J.R., W.E. Doll, and W.A. Mandell, 2005, An evaluation of methods and available software for seismic refraction tomography analysis, JEEG, V. 10, No. 1, pp. 21-34.

Sirles, P., A. Rock and R. Zhang, 2005, NDT technologies and unknown foundations, *in* Presentations and Notes, FHWA Unknown Foundation Summit, Lakewood, Colorado, U.S. Department of Transportation

Zhang R. and S. Sture, 1995, Discrete Element Particles Analysis at Low Stress States, in Proceedings of the 10th ASCE Engineering Mechanics Specialty Conference.

Zhang, R. and S. Sture, 1996, Flexible Boundary for Discrete Element Simulation of Granular Assemblies, in Proceedings of the 11th Engineering Mechanics Conference.

Zhang, R., 1996, Discrete Element Modeling of Granular Materials Under Biaxial Conditions, Ph.D. dissertation submitted to the Faculty of the Graduate School of the University of Colorado.