A study of the geotechnical imaging techniques using seismic geotomography

L'étude de la technique de l'image-géotechnique utilisant la géotomographie séismique

Y. S. Paik & Y. J. Mok – *Department of Civil Engineering, KyungHee University, Korea*
S. B. Im – *DongBu Engineering Co. Ltd, Research Center, Korea*

ABSTRACT: A operational tomography system was developed for geotechnical site characterization in rock materials. A pair of piezoelectric transducers and a tomographic imaging techniques were demonstrated in a laboratory environment.

RESUME: Le système tomographique opérationnel a été dévelopé pour le mesure des caractéristiques géotechniques des matériaux rocheux dans le chantier. Une paire de tranducteurs piézoélectrique et la technique d'image tomographique ont démontré dans l'environnement de laboratoire.

1. INTRODUCTION

Detailed evaluations of subsurface material properties are required for underground space projects including tunnel, metros and caverns for storages and environmental treatment. In addition to borehole exploration, an enhanced methodology for more detailed profiling should be developed to keep up with the recent strides in underground space technology. The task can be accomplished by adapting tomographic imaging methodology to data acquired using modified versions of standard in situ seismic exploration techniques.

In situ seismic testing techniques, including crosshole and spectral-analysis-of-surface-waves(SASW) has been employed by geotechnical engineers for successful diaracterization of geotechnical sites(Mok 1987, Stokoe et al. 1988). Tomographic imaging procedures provide a non-invasive means to evaluate spatial distribution of heterogeneous materials. The tomography applications considered herein utilize measurements of the travel times of seismic waves to infer subsuface materials.

In crosshole tests, the travel time data are collected by setting the source and receivers at the same depths and inverted into one dimensional stiffness profiles. In tomographic imaging, crosshole measurements are repeated by simply varing the source-receiver elevation offset in adjacent boreholes so as to yield the travel time data over inclined raypaths, as well as horizontal ones. The data obtained from the overlapping raypath sets are then tomographically to yield a two dimensional distribution of subsurface material stiffness.

The tomographic techniques has been successfully implemented by the medical diagnosis, petroleum and mining communities. Geotechnical applications have been rather limited to date. Very recently, a seismic data acquisition was developed by a number of research groups(Witten and King 1990, Roblee 1990).

The primary objective of the paper is to develop an operational tomographic imaging system which is well suited to geotechnical characterizations for underground space projects. In the paper, Development of the piezoelective transducers and tomographic imaging software will be discussed.

2. DATA ACQUISITION SYSTEM

The system was developed for precise measurements in rock materials and was, thus, tuned to generate higher frequency seismic waves than conventional mechanical crosshole sources. The key requirement of the system is the capability to generate SH-wave as well as p-wave. The desired additional requirements included the ability to fit into NX-size (76 mm in diameter) boreholes and operate in inclined boreholes as well as verical holes, simplicity of design and maintenance, and ease of data acquisition. The system was upgraded from the one developed at the University of Texas at Austin(Roblee, 1990) by upgrading mechanical and electrical parts towards generating more seismic energy and easier maintenance.

2.1 *Conceptional transducer design*

The capacitive behavior of a piezoelectric material is utilized in generating and monitoring seismic pulses. To generate seismic pulses, the piezo electric elements are charged by electrical energy and shorted to release the stored strain energy into the rock materials. In receiving seismic waves, the aforementioned energy conversion is reversed. Piezoelectric elements generate an electric field in response to mecanical stresses propagated from the source.

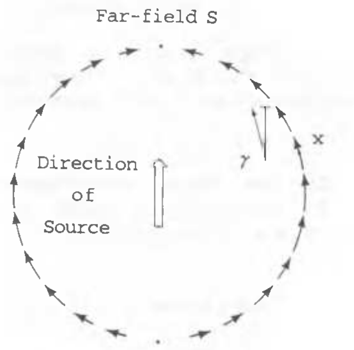
2.2 *SH - wave generation*

In a homogeneous, isotropic, unbounded medium, the far-field s-wave(AKi & Rechards, 1980) can be described by

$$u_i^s(x,t) = \frac{1}{4\pi\rho {v_s}^2}(\delta_{ij} - \gamma_i\gamma_j)\frac{1}{r}x_o(t - \frac{r}{v_s}) \qquad (1)$$

where u_i^s = displacement vector of s-wave
x = position variable
t = time variable
ρ = density
γ = direction cosine
δ_{ij} = Kronecker delta
r = source - receiver distance
x_o = point source
v_s = shear wave velocity.

This equation implies that the amplitude of far-field shear wave is portional to the cosine of the angle between the force direction and the direction of receiver(see Figure 1.). Thus horizontally polariged shear waves can be generated and monitored by simply orientating both the source and receiver perpendicular to the alignment of the borehole array.



Note : The amplitude is maximum when $\gamma = 0^\circ$.
The amplitude is zero when $\gamma = 90^\circ$.

Figure 1. Variation of s-wave amplitudes with different orientations

2.3 *Source and receiver transducers*

The main goal of the design was to devise a simple, radially oriented, piezoelectric stack system which fits into a NX-size(76 mm in diameter) holes.

The conceptional depiction of the transducers is shown in Figure 2. The main parts included the backing mass and piezoelectric element stack housing assembly, the clamping system, electronics chamber and the adapter to orientation rods.

Seismic energy delivered is limited by the amount of electrical energy stored in piezoceramic stacks, which is, in turn, proportional to volume of material used. Because of borehole size limitation, two 30 mm-long stacks of piezoceramic discs of a 38 mm in diameter were wired in parallel.

Good coupling of the transducers against the borehole wall is essential to generating and monitoring seismic waves. Coupling is accomplished by means of inflating an air bag which push the coupling shoe against borehole wall with a high normal force. This system was chosen because it provides easy remote control of clamping action and is fast, inexpansive and easy to be replaced. The air bag is a 25 cm-long piece of regular fire hose with a specially-designed fitting. The air bag also acts as a soft isolator which decouples the stack housing from the remaining portions of the source.

The downhole electronics package is housed in the electronics chamber. The major components for the source are a high voltage SCR switch, a tuning coil, and a damping circuit. The electronics for the receiver consists of a simple 20 dB gain amplifier used to assure good signal to noise ratio.

As mentioned before, proper control of the source and receiver orientations is very critical in measuring SH-wave as well as p-wave. The orientation is controlled by specially manufactured orientation rods.

Any recording equipment can be used as long as it meets the requirements including a sufficiently fast sampling frequency to obtain the desired time domain resolution, a means to store large quantities of data, and a high degree of reliability and urability to withstand the field environment.

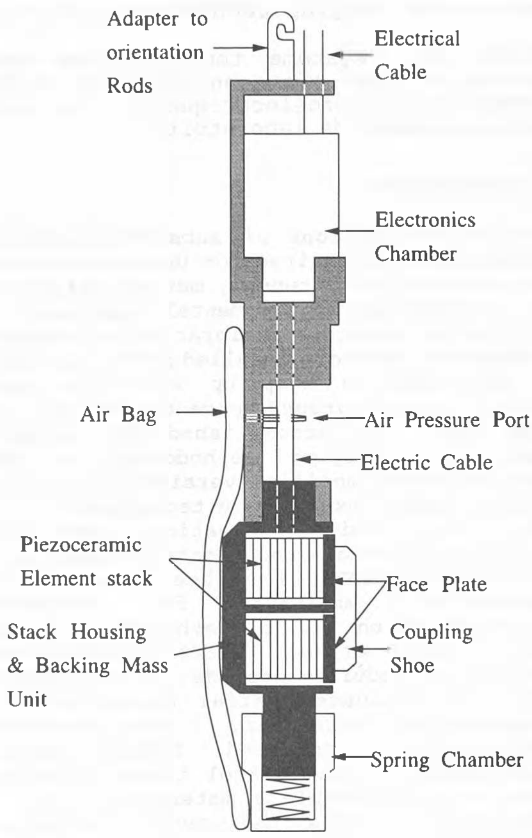


Figure 2. Schematic diagram of major components of piezoelectric transducers

3. SOFTWARE

The core algorithms for tomographic imaging consists of back projection technique and the generalized inverse method. The initial smooth image is created by back projection technique and further refined by the generalized inverse method which utilizes singular-value decomposition of the data kernel matrix(Menke, 1984).

The image region between the source and receiver boreholes is discretized into pixels (rectangular elements). The slowness (inverse of wave velocity) of each pixel forms the model vector, **m**. The data vector, **d** is the measured travel times of all ray paths. The formulation between **m** and **d** can be given by

$$\mathbf{Gm} = \mathbf{d} \tag{2}$$

where **G** is the data kernel matrix whose elements are the intersection lengths of ray paths with pixels. The tomographic problem is generally mixed-determined and the data Kernel matrix **G** is decomposed as

$$\mathbf{G} = \mathbf{U}_p \Lambda_p \mathbf{V}_p^T \tag{3}$$

where $\mathbf{V}_p$ and $\mathbf{U}_p$ are the non-null eigenvectors of the model and data space respectively and Λ_p is the diagonal eigenvalue matrix. The generalized inverse $\mathbf{G}^{-g}$ is the constructed as

$$\mathbf{G}^{-g} = \mathbf{V}_p \Lambda_p^{-1} \mathbf{U}_p^T \tag{4}$$

The estimates for the model parameters, $\mathbf{m}^{est}$ are in the form

$$\mathbf{m}^{est} = \mathbf{m}_0 + \mathbf{G}^{-g} [\mathbf{d} - \mathbf{Gm}_0] \tag{5}$$

where $\mathbf{m}_0$ is the initial smooth backprojected image.

The algorithms were coded in fortran and compiled by Lahey fortran compiler. The code can handle up to 28 × 28 pixels.

4. LABORATORY CUBE

The behavior of the software was examined by the data set obtained from a laboratory cube designed to simulate the solid rock including an inclusion of highly cracked zone. The cube consists of a concrete square block approximately 1.8 m in each dimension surrounding a cement-sand square prism approximately 0.6 m × 0.6 m × 1.8 m. Solid rock was simulated by the concrete surrounding a cement-sand prism, which is analogous to the cracked zone. The cross section of the cube is depicted in Figure 3.(a). The concrete and cement-sand were characterized by small-scale crosshole tests and free-free resonant tests of cylindrical specimens. P-wave velocity of concrete and cement-sand were 4000 m/sec and 2500 m/sec, respectively.

The cross section were discretized into rectangular 9×9(81) pixels and 162 ray paths were used to form the data set of initial arrival travel times.

5. RECONSTRUCTED IMAGES

The resolution of a tomographic image is a function of the angular ray coverage of the region of interest. The most desirable geometry for good angular coverage is to surround the region completely as is done in medical imaging(called "full access" geometry). However, a more feasible configuration in geotechnical applications is that a region is bounded by two boreholes only (called "pure crosshole" geometry).

To evaluate the performance of the code with putting this aspect aside, cross-section image of the cube was reconstructed with 2 sets of data collected with full access geometry. The cross section was discretized into 9×9 pixels and 162 ray paths of full access coverage were used to successfully reconstruct the image as shown Figure 3.(b).

With the data collected from left and right side boundaries in Figure 3.(a), the image was distorted horizontally(Figure 3.(c)). This fact illustrates the coherent problem caused by incomplete ray path coverage in geotechnical applications rather than limitations of algorithm itself.

6. CONCLUSIONS

A operational tomography system was developed for geotechnical site characterization in rock materials. The piezoelectric transducers can provide more precise measurements of material stiffness than conventional mechanical sources. SH-wave measurement capability of the system can provide a more complete characterization for underground space projects. A tomographic imaging technique which utilizes singular-value decomposition of the data Kernel matrix was demonstrated by reconstructing the cross-sectional images of a laboratory concrete/cement-sand cube.

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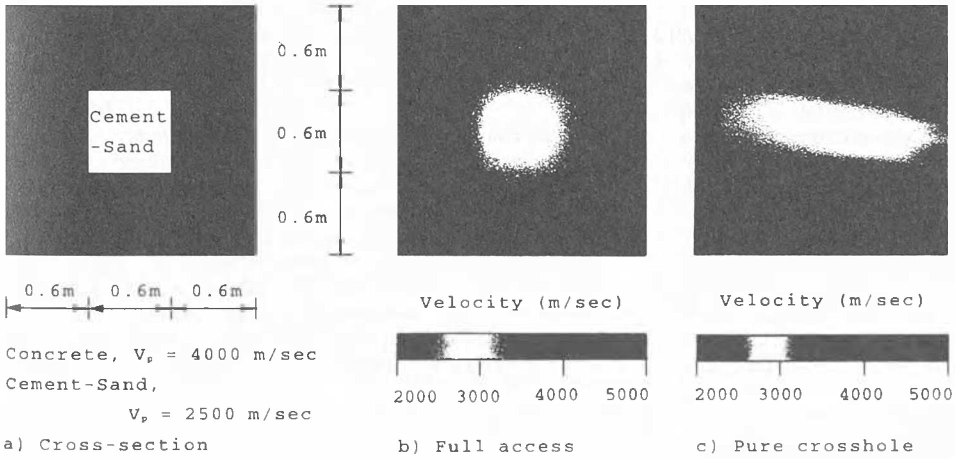

a) Cross-section b) Full access c) Pure crosshole

Figure 3. Cross-section and its reconstructed images of the cube

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