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Original Article

# Detecting near-surface objects with seismic traveltime tomography: Experimentation at a test site

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## Abstract

In environmental and engineering studies, detecting shallow buried objects using seismic reflection techniques is commonly difficult when the acquisition geometry and frequency contents are limited and the heterogeneity of the subsurface is high. This study demonstrates that such near-surface features can be characterized by taking advantage of P-wave traveltimes of seismic data. Here, a seismic experiment was conducted across a buried drainpipe series, the main target, with the goal of imaging its location. Tomography is implemented as an iterative technique for reconstructing the P-wave velocity model from the first-arrival traveltimes. To study the reliability of the method, a set of starting model was tested and a synthetic data was generated. After evaluation and selection of the best model, the resulting image was interpreted. The low velocity zone in the tomographic image coincides well with the location of a drainpipe series and surrounding altered ground due to its installation. The existence of buried objects at the test site confirms and demonstrates the potential of the method application.

Keywords: seismic tomography, traveltime, inverse theory, near-surface object

## 1. Introduction

Seismic reflection technique is a geophysical method widely applied to address environmental and engineering problems because of its ability to produce high-resolution images of the upper 100 m of the subsurface (e.g. Bradford *et al.*, 1998; Bradford and Sawyer, 2002; Francese *et al.*, 2002; 2005; Juhlin *et al.*, 2002). Among many of these cases, high-resolution images have been successfully reconstructed using relatively short source and receiver intervals. Even if the spatial sampling is dense enough, however, the information in the uppermost part of seismic section is often lost due to the acquisition geometry and data processing. In addition, obtaining satisfying seismic images are difficult, especially when the subsurface is characterized by strong velocity varia-

\* Corresponding author. Email address: sawasdee.y@psu.ac.th tions with heterogeneities close to the seismic signal wavelength (Grandjean and Leparoux, 2004). A number of studies have shown that such problems can be solved by seismic tomography, which takes advantages of the first arrival time of reflection data (e.g. Heincke *et al.*, 2006; Schmelzbach *et al.*, 2007; Yordkayhun *et al.*, 2009).

Like medical X-ray photography and Nuclear Magnetic Resonance (NMR) imaging (Gordon *et al.*, 1970; Phongpaichit *et al.*, 2005), tomography is a nondestructive technique imaging differences in physical properties of internal structures based on a set of observed data. In seismic traveltime tomography, the technique normally refers to the measurement of elastic wave traveltimes that pass through a subsurface medium. Tomographic images, the resulting images of the velocity variation in complex geological environments, are associated with variations in traveltimes.

Seismic tomography plays an important role in a broad range of environmental and engineering applications, for example, identifying shallow fracture and fault zones (Morey and Schuster, 1999; Marti *et al.*, 2002; Bergman *et al.*, 2004; 2006), detecting cavities and buried objects (Grandjean and Leparoux, 2004), mapping contamination sites (Zelt *et al.*, 2006), and investigating archaeological features (Polymenakos and Papamarinopoulus, 2007). Nevertheless, a successful application in many cases depends on reliable resulting models. The ability to obtain such a model relies on several factors, e.g. sufficient ray coverage and solution of the non-linear problems (Kissling, 1988). Numerous techniques have been developed for improving the model's reliability, such as checking of the picking error and data quality, selection of model parameterization and starting model, the model and data constraints, and static correction requirements (Lanz *et al.*, 1998; Chang *et al.*, 2002).

This study presents the results of a tomographic inversion of a shallow seismic reflection experiment, which aimed to image the P-wave velocities across a buried drainpipe series. The objective of the study is to locate the position of buried drainpipe. It serves as preliminary test for the efficiency of the method in detecting heterogeneities in the nearsurface structures. Here, the tomographic inversion on a set of initial models was tested and the algorithm performance was evaluated in order to study its robustness and possible associated difficulties. Interpretation of the tomography results attempt to locate near-surface velocity anomalies associated with the exactly known target location. Consequently, this work demonstrates a case study related to environmental and engineering application, for instance, the detection of shallow fault, sinkhole, cavities or pipes.

## 2. Theoretical background of tomography

The tomography technique relies on the principles of the inverse theory (Menke, 1989). A suitable image (model) of physical properties is constructed based on a set of measured data through a mathematical framework providing by the inverse theory. A general form of the relationship between data and model parameters can be written as following

$$\mathbf{Gm} = \mathbf{d} \tag{1}$$

where  $\mathbf{d}$  is the vector of the observations,  $\mathbf{G}$  is the kernel matrix that relates the model to the observation, and  $\mathbf{m}$  is the vector containing model parameters.

The inversion process involves computing the model **m**. A solution is often found by using a least squares approach (Menke, 1989). However, the problem should be constrained or regularized in some way to control the inverse solution to be stable. Many of the geophysical inverse problems are non-linear and have non-unique solutions; especially seismic traveltime tomography is a non-linear problem in the view point that the seismic ray bending itself obeys the unknown velocity structure. A standard technique for dealing with this is to linearize the traveltime equation

about some reference model (Kissling, 1988; Benz *et al.*, 1996) and iterate. A variety of iterative solvers, such as ART (Peterson *et al.*, 1985), SIRT (Trampert and Levequ, 1990), and conjugate gradient methods, e.g. LSQR (Paige and Saunders, 1982) have been available to be implemented in matrix inversions.

In seismic traveltime tomography, the method of determining subsurface velocities consists of following main steps (Rawlinson and Sambridge, 2003):

1) Model parameterization, defining the seismic structure in terms of a set of unknown model parameters,

2) Forward calculation, simulating the first-arrival traveltime of seismic waves by solving the wave equation,

3) Inversion, adjusting the model parameter values (the velocity structure) with the object of minimizing the error between the calculated and picked traveltimes, and

4) Analysis of solution robustness.

The relationship between an unknown velocity model and the observed traveltimes of the seismic waves is given by the path integral for the traveltime (t) for one source-receiver pair:

$$t = \int_{l\{s(r)\}} s(r) dl \tag{2}$$

where s(r) is the slowness (inverse of velocity) and dl is the differential length, l(s) represents the raypath which is a function of s(r).

In the model parameterization, an earth model is discretized into regular slowness cells of unknown constant slowness value. The forward calculation of traveltimes is performed on a uniform grid by solving a first-order finitedifference approximation of the eikonal equation (Podvin and Lecomte, 1991; Tryggvason and Bergman, 2006). The eikonal equation is a ray-theoretical approximation to the scalar wave equation, representing wavefronts of constant phase. This is expressed by:

$$\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2 = \frac{1}{v^2(x, y, z)}$$
(3)

Equation 3 provides the traveltime T(x,y,z) for a ray passing through a point (x,y,z) in a medium with velocity v(x,y,z). Once the traveltimes to all receivers (or shots) are known, the raypaths are obtained by ray tracing backward from the receiver locations perpendicular to the wavefronts (Vidale, 1988).

Experiences from near-surface application for a tillcovered bedrock environment (Bergman *et al.*, 2004) have revealed that including a static term in the linearized traveltime equation has a great benefit when the unconsolidated layer were causing distortions in the final velocity model. Linearizing Equation 2 about a starting model results in the equation

$$r_{ij} = t_j + \sum_n^N \frac{\partial T_{ij}}{\partial u_n} \Delta u_n, \qquad i = 1, \dots, I, \qquad j = 1, \dots, J \quad (4)$$

where  $r_{ij}$  is the traveltime residual between source *i* and receiver *j*,  $t_j$  the static shift at receiver *j*,  $T_{ij}$  is the traveltime between the source and receiver, and  $\Delta u_n$  the slowness perturbations in each cell passed by the ray. In vector form Equation 4 is written as

$$\mathbf{T} + \mathbf{D}\Delta \mathbf{u} = \mathbf{r} \tag{5}$$

where  $\mathbf{r}$  and  $\Delta \mathbf{u}$  are matrix representations of the data residuals and slowness perturbations,  $\mathbf{D}$  is the matrix of the partial derivatives, and  $\mathbf{T}$  is the matrix of all the static shifts.

The computed static term  $t_j$  is a surface consistent term, i.e. a combination of a receiver and all the involved source location static shifts. Thus, every computed static term  $t_j$  may be expressed as

$$t_j = r_j + \sum_i^I w_i s_i \tag{6}$$

where  $r_j$  is the receiver static term,  $s_i$  are all the *I* source static terms involved in computing  $t_j$ , and  $w_i$  is a weighting parameter (here we simply used 1/I for weights). The system of equations to solve may thus be written in matrix form as

$$\begin{bmatrix} \mathbf{t} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{w} \\ \mathbf{I} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{s} \end{bmatrix}$$
(7)

where, **p** contains the up-hole times (zeros in case of no up-hole times), the **I**'s are identity matrices, and **t**, **r**, **w** and **s** are the vector expressions of Equation 6.

After separation of variables (see Bergman *et al.*, 2006 for details), the static terms are solved separately and the final system of equations to solve for the slowness perturbations is

$$\begin{bmatrix} \mathbf{D}'\\ \lambda \mathbf{L} \end{bmatrix} \Delta \mathbf{u} = \begin{bmatrix} \mathbf{r}'\\ \mathbf{0} \end{bmatrix}$$
(8)

where L is the matrix of the Laplacian smoothing operator, controlled by the scalar  $\lambda$ . A high value of  $\lambda$  implies a larger amount of smoothing.

Equation 8 is a linearization of the non-linear problem that will be used for inversion. In this study, the solutions are estimated in least-squares sense by iteratively solving algorithm of the Paige and Saunders (1982) conjugate gradient solver LSQR.

We used *PStomo\_eq* algorithm (Tryggvason *et al.*, 2002) for tomographic inversion. In model parameterization, a grid size of 1x1 m provided for a large fold (rays crossing per cell) while still small enough to reconstruct interesting details. The inversion was run over seven iterations, gradually relaxing the weight on the Laplacian smoothing constraints ( $\lambda$  in Equation 8), in order to obtain a minimum structure model and test the convergence to the final solution. The steps for every iteration are outlined in Figure 1.

This sequence is repeated until a total root mean square (RMS) data misfit matching the estimated data error is obtained.

## 3. Seismic Experiment

#### 3.1 Data acquisition

A seismic reflection experiment was conducted across a series of concrete drainpipe at a test site. The profile is oriented perpendicular to 6 drainpipes on flat ground surface topography (Figure 2a). Each concrete drainpipe has a diameter of 1 m, buried at about 2 m depth in highly compacted subsurface underlying sand and gravel overburden. The seismic reflection profile was acquired using a shot through scheme. 24 recording stations and 22 source points were deployed. The geophone spacing and the source spacing were set to 1 m and 2 m, respectively (Figure 2b). This configuration forms a 12 maximum fold coverage along the 45 m length of the profile. The seismic source was a sledgehammer strike on an aluminum plate on the ground and 5-10 repeated shots at the same position were stacked in order to enhance the S/N ratio. The data were recorded using 0.25 ms sampling interval with 350 ms record length. Acquisition parameters are summarized in Table 1.

## 3.2 Traveltime picking

The first step in tomography processing is picking the first-arrival traveltimes since they served as the input parameters for the inversion procedure. 528 traveltimes with a maximum recorded offset of 36 m were automatically picked from the data using Globe Claritas software (Ravens, 2007). A shot gather with the picked first-arrival traveltime is illus-



Figure 1. Flow chart showing the iteration process of tomographic inversion.



Figure 2. Surface topography and drainpipe series in the test site (a) and profile geometry (b). Dashed area highlight the area in (a).

Table 1. Acquisition parameters and equipment.

| Parameter   | Detail   |
|---|--|
| Energy sources<br>Shots per source point<br>Spacing                 | 10 kg sledgehammer 5-10<br>2 m                       |
| Receivers<br>Natural frequency<br>Spacing                           | Vertical, 14 Hz (single)<br>1 m                      |
| Profile<br>Offset Min/Max<br>Maximum fold                           | 1/36 m<br>12   |
| Recording<br>Recording system<br>Record length<br>Sampling interval | Geometric SmartSeis 24 channels<br>350 ms<br>0.25 ms |

trated in Figure 3a. Note that the deeper part of model may be less accurate due to a small portion of far-offset traveltimes (Figure 3b).

Quality control of the traveltime picks is required for a reliable inversion prior to the construction of the tomogram. This is done by checking the S/N of data and verifying that the reciprocity condition is satisfied. Although airwaves and ground roll dominate on the seismic records, these events did not cause serious problems since the first-arrival traveltimes were rather accurately picked at onsets of the signals in the first automatic picking. However, uncertainties in the picking may encounter in far offset traces where the disturbance of ambient noise is significance. For more accurate picking, these parts of data were manually refined by visual inspection.

Quantitative estimation of picking accuracy is about a quarter of the dominant period where two waves add constructively and can not be distinguished from each other if they arrive within this interval (Zelt *et al.*, 2006). Following this criterion and power spectrum analysis (Figure 3c), the dominant frequency of the data varies from 100 to 150 Hz, suggesting the picking error would be approximately 2-4 ms.

## 3.3 Starting models

A realistic starting model is needed to avoid unreliable velocity models due to possible violation of linearization assumption and to check the robustness of the method corresponds to the distribution of raypaths in the velocity models. In this study, a 1D starting model for traveltime tomography is extracted from the traveltime curves (Figure 4a). The first-arrival recorded on the near offset traces ( $\leq 5$  m) of some shots is characterized by apparent velocities of about 500-700 m/s. For larger offset, the traveltime curves start to diverge and match the wide range of apparent velocities (about 1,800-3,500 m/s). This may indicate a strong velocity variation in the test site. Note that the existence of



Figure 3. (a) Common shot gather from data set and first-arrival traveltime picks are denoted by the red dot. (b) Offset distribution histogram. (c) Power spectrum of data.



Figure 4. (a) Traveltime-distance curve of selected shots. (b) Set of 1D starting model.

local traveltimes delay in some shot records is evidence of a possible low velocity features.

Four starting models, layered and gradient velocity models, were tested (Figure 4b). Model 1 and 2 represent the velocity gradient model, where velocity increases with depth with difference gradient. Model 3 represents the layered earth model, where velocity is constant within each layer. Model 4 represents the layered earth model, where velocity increases with depth within each layer. Model 3 and 4 are also representing the case where a low velocity unconsolidated sediment cover exists.

# 4. Results and Discussions

#### 4.1 Analysis of solution quality

RMS data misfit is a crucial indicator for evaluating the model convergence and stability. Tracking the RMS data misfit during the inverse procedure has shown that for all models stability on the solution occurred after the 6<sup>th</sup> iteration (Figure 5). A plot of maximum traveltime residual versus iteration number is also shown in Figure 5. Each model yields very close final traveltime residual of about 3 ms, which is slightly smaller than our maximum estimated picking error of 4 ms. Tracking also found that differences in the starting models resulted in different final models, despite the similar-



Figure 5. Plot of RMS data misfit and maximum residual versus iteration number.

ity in the RMS data misfit between the final models. We get insight into the non-uniqueness of the solutions and the effect of the non-linearity of the problem by this observation, suggesting that *apriori* information and constrains may be required to obtain a more reliable model. Based on the fact that the RMS data misfit of the starting model in Model 3 and 4 are less than in Model 1 and 2, the presence of a low velocity cover is likely to be a reliable model. In addition, the difference in model convergence between Model 3 and 4 is very small, implying that the inversion is relatively stable.

## 4.2 Tomography results

Figure 6 shows the tomographic images presented as distribution of seismic velocity along the profile together with their ray density through each cell in the images (only for cells crossed by rays are displayed). In general, all models illustrate almost similar velocity distributions, except the ray coverage and low velocity anomaly. The tomographic images reveal two subsurface layers. The first layer is an overburden with a seismic wave velocity of about 600-800 m/s. The thickness of this layer is about 1-2 m. The second layer has a broad range wave velocity of 1,500-3,000 m/s. The velocity variations within this layer suggest a significant lateral contrast in the medium. The thickness of this layer extends to the bottom of the image. The middle part of the tomographic images is characterized by lower velocity values for both layers. Within this zone, seismic velocities are reduced by 20-30% from the host material velocities.

The ray density section is useful for verifying the capability of the raypath geometry to resolve anomalous velocity distribution in the tomographic image. Normally, the more rays in the imaged region are sampled the more reliable the model velocities are (Moret *et al.*, 2006). The ray coverage in Model 4 is slightly denser and has a better distribution than in the other models, supporting that the resulting model is more reliable. The effect of the low velocity anomaly on the wave propagation is observed on the section (about 2-3 m depth) where rays avoid the low velocity anomaly. This information may be useful in the tomography interpretation since the low ray density zones and abruptly change in velocity gradient zones (e.g., fault and cavity) are correlated (Flecha *et al.*, 2004).



Figure 6. Resulting models obtained from four different starting models in Figure 4 (left panel) and their ray density distribution (right panel).

#### 4.3 Synthetic model analysis

In order to check the inversion process and to verify if we could resolve a near-surface object, noise-free synthetic data were generated from a true model shown in Figure 7a. In this model, a square-shape object with the length of 7 m and the depth of 3 m with velocity of 500 m/s is embedded in the two-layer medium. This object is assumed to be the geometry of buried drainpipe series in the subsurface. The low velocity cover (700 m/s) with a thickness of 2 m represents the weathering or unconsolidated upper layer. The high velocity in the deeper layer represents the host material or highly compacted ground. In order to present a realistic scenario, the acquisition geometry and inversion procedure are exactly the same than in the real case study.

Figures 7b and 7c show the final model and the ray coverage of the synthetic data, respectively. Compared with the real case, the pattern of tomographic images appears to match reasonably well. The low velocity anomaly has been correctly located, even if the transition to this anomaly is not sharp. Note that the applied smoothing constraints may counteract the creation of a sharp velocity contrast in the model. This synthetic model demonstrates the stability of the tomography algorithm, leading to greater confidence in the results.

# 4.4 Correlation with conventional refraction analysis and seismic section

Based on previous assessment, Model 4 is selected for further interpretation. The tomography results and velocity-depth section deduced from the conventional refraction interpretation, corresponding to depths less than 10 m, were compared. It has to be realized that conventional refraction analysis cannot image the presence of possible low velocity layers (hidden layer problem), whereas finite difference techniques for forward travel time calculations introduced in tomography allow for a reliable calculation of the least time path in complex velocity structures where traditional shooting or ray bending techniques have limits (Grandjean and Leparoux, 2004). It is observed that the estimated velocity values and depths of the two main layers from the conventional refraction analysis agreed well with the values of the tomographic image. There is also evidence of a collapsed interface in the middle of the velocity-depth model due to this anomaly (Figure 8b).

Beside seismic tomography, seismic reflection data were processed using the commercial software package Globe Claritas (Ravens, 2007) to construct the seismic stacked section (Figure 8c). Processing details are not described here. As expected, the uppermost 10 m depth in the seismic section



Figure 7. Resulting model (b) and the ray density distribution (c) of synthetic data obtained from the true model in (a).



Figure 8. (a) Tomographic image with interpreted buried objects zone. (b) Velocity-depth model from refraction analysis. (c) Seismic stacked section overlain by tomogram. Square marks the discontinuity of reflection horizons.

is poorly resolved. Clear reflection horizons are observed at about 10-25 m depth in the stacked section. Note that the discontinuities at both ends of the section are due to low fold coverage. Even though there is high fold coverage in the middle part of the section, it is likely that the reflector discontinuity is due to the affect of near-surface heterogeneity. This suggests that static correction is an important step to be considered in reflection data processing.

Integrating the tomographic image, velocity-depth model and stacked section, the near-surface features at the test site can be interpreted. The low velocity layer with the thickness of 1-2 m may correspond to unconsolidated sediments cover of sand and gravel. The underlying high velocity layer is interpreted to be highly compacted rock fragments and gravel. The drainpipe series, which act as air filled cavity is correlated well with the low velocity zone in the middle of the tomographic image (anomaly marked in Figure 8). However, the model shows an anomaly with an unfocused shape (the transition to the central velocity low is not as sharp). This is qualitatively consistent with the ground disturbance due to the drainpipe installation. Note that we neglect the effect of concrete because it thickness is under the resolution limits of the data.

## 5. Conclusions

After evaluating the inversion performance and selecting the reliable model, following general conclusions can be drawn:

1) It is possible to image the strong velocity variations by means of seismic traveltime tomography. The consistent anomaly that appears to be the location of drainpipe series and surrounding disturbed ground is characterized by a low velocity zone at about 2-3 m depth.

2) The results are in agreement with reality, although non-unique solutions were found. The tests carried out on this data set pointed out the restrictions to be taken into account, particularly picking accuracy, suitable starting model, and static corrections that could improve the tomographic image.

3) Based on the findings and confidence from this study, the proposed method can be considered as an effective tool for adressing environmental, engineering as well as archaeological problems, e.g., detection of shallow fault, cavity, pipes, and tunnels.

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