Feasibility study on joint tomography of refraction and reflection seismic waves for geotechnical purposes: a preliminary result

Ruhul Firdaus¹*, Gestin Mey Ekawati¹, Cahli Suhendi¹
¹ Department of Geophysical Engineering, Institut Teknologi Sumatera (ITERA), Lampung, Indonesia
*Corresponding email: ruhul@tg.itera.ac.id

Abstract. Many developing regions are subject to infrastructure magnification thus green-sustainable infrastructure has always been a relevant concern for most regulators and engineers. In order to support better urban planning, civil engineering operations, and environmental studies, an ample supply of information regarding the neighbouring environment is a must. This includes the information from the Earth’s subsurface, particularly the mechanical properties of soil and rock, on which the planning or action is executed. Complementarily, geophysical measurements utilizing the active seismic method can effectively provide an accurate approximation of the properties. This method includes generating seismic waves using the non-invasive artificial seismic source which then be collected on the Earth’s surface by a number of detectors called geophones. The recorded seismic waves bring information about the medium through which they propagate. They can provide the mechanical properties of the medium after applying some sequences of data interpretation techniques. Conventionally, this is done using only one type of seismic wave, either the refracted or reflected waves. In this study, we build a new procedure incorporating these two types of seismic waves to refine the inferred model. The result shows a promising improvement of the P-wave velocity model in terms of its resolution.

Keywords: geotechnics, seismic, joint tomography

1. Introduction

Earth provides prosperity, a place to live, and natural resources for mankind. At the same time, it also may cause dramatic damage in a minute to what we have built forever. Almost every place on Earth is habitable, but not all of them are comfortable. We, for a very long time, have been engineering our place to suit our comfort as well as to support our activities and ambitions. Now, we are in the situation to ensure the continuity of our comforts or activities by developing the concept of green-sustainable infrastructure. These kinds of infrastructure encompass broad initiatives focusing on energy, water, and land management. Apart from its overlapping benefits from physical, environmental, economic, and social perspectives, sustainable infrastructure also has a wider perspective as an economic magnification, community welfare, and financial interests.

Developing such infrastructure, regulators or engineers need relevant information on the neighbouring environment on which the planning and actions are executed. This includes an understanding of the Earth’s subsurface such as the mechanical properties of soil and rock. By using the principles of physics and chemistry, engineers use this information to modify the characteristics and properties so it can support civil infrastructure. Tying micropiles, for instance, are conducted to improve infrastructure grounding. Geophysical measurements
have been used for these purposes as they are cost-effective, efficient, and accurate to delineate information from boreholes utilized for site characterization. For example, in some places, this characterization involves the identification of softer soils, fractured rocks, faults, caverns, or sinkholes. One of the geophysical surveys that suit these purposes is active seismic measurement.

Active seismic measurement activities generate seismic waves that travel through the Earth. Some of them are refracted and reflected back to the surface. These waves are then captured by detectors planted on the ground surface, called geophone. Geophysicists use these waves to study Earth’s material from centimetres to thousands of kilometres. Utilization of this method in geotechnical engineering is abundant especially by incorporating seismic tomography technology.

Despite the fact that tomography is developed initially for medical purposes and it has become the most advanced technology for helping medical diagnostics, tomography is also very powerful in geophysics [1-3]. The use of technology is ranging in all scales and fields. For example, it has been used to evaluate the whole Earth [4]. Laboratory samples (e.g., [5,6]), earth structures (e.g., [7]), archaeology (e.g., [8-10]), and geotechnical purposes such as study on volcanic rocks in Turkey [11], permafrost in Canada [12], site characterization [13], and imaging an unstable embankment [14]. Linking seismic tomography and geotechnical site assessment is sufficiently described in [15]. However, the existing studies are heavily relying on one type of seismic wave namely the refraction wave. In this paper, we demonstrate the utilization of both refraction and reflection seismic travel-time data to get a better P-wave velocity model of the subsurface.

2. Method

Since the recorded seismic waves travel through a medium, they contain the mechanical properties of the medium. These properties can be extracted from the data after some sequences of interpretation techniques. Conventionally, this is done using only one type of seismic wave, either the refracted or reflected waves. Refracted and reflected waves are jointly used in tomographic schemes as described in [16] and [17].

In this study, seismic waves are excited using a sledgehammer as source energy after 24 geophones are lined by one-meter intervals using data acquisition layout as illustrated in Figure 1. The sources are also lined parallel to receivers at a one-meter radius and shifted every one meter for each recording. In other words, the 24 receivers are fixed while the source is moving. The recording is done for each shot using a 0.5-millisecond sampling rate and a 200-millisecond record length.

**Figure 1.** Data acquisition layout showing the static receiver line and source movement.
In order to conduct a feasibility study on the applicability of joint refraction-reflection tomography in geotechnical scales, a simple yet representative field is chosen. The data acquisition scheme and parameters shown in Figure 1 is applied to an obvious environment which clearly shows horizontally-layered soil and bedrock. The uppermost structure is soil overlaying nearly horizontal pyroclastic, weathered-bedrock. Even though the bedrock has experienced some kind of weathering, it still has the strength. Soil is much weaker in comparison to the bedrock hence we expect to see this structure from the seismic application. Field deployment and soil-bedrock structure are indicated in Figure 2.

From this survey, we acquired some seismic wave recordings. Selected data samples are shown in Figure 3. The first arrivals are analyzed using the intercept time [18] and the plus-minus method [19]. This first step results in a refraction plane model which is used as a reference to generate an initial model for tomography inversion. The reflected waves are also analyzed to get reflection time data. This step inherits difficulties as the first reflection is barely distinguishable due to the ground roll waves and their backscattering. To overcome this problem, hypothetical reflection times from the initial model is generated by assuming a reflector layer. This hypothetical reflection time data act as guidance to perform time picking from the real data. Once the reflection time is attempted, the joint tomography inversion is performed by inverting the ray equation of refraction and reflection seismic. In the forward data calculation, a pseudo-bending algorithm [20] is utilized and is updated every iteration unless the ray of reflection wave is assumed to be a straight line for all iterations. Finally, inversion is done using nonlinear least-squared inversion where the objective function of minimizing both misfit and penalty model is solved using the gradient method as described by [21] and [22]. The model updating algorithm is done iteratively using the following equations.

\[
\delta m = \left[ G^T C_d^{-1} G + \varepsilon C_m^{-1} + \eta D^T D \right]^{-1} G^T C_d^{-1} \delta d
\]  

\[
\left( \begin{array}{c}
C_d^{-1/2} G \\
\sqrt{\varepsilon} C_m^{-1/2} \\
\sqrt{\eta} D
\end{array} \right) \delta m = \left( \begin{array}{c}
C_d^{-1/2} \delta d \\
0 \\
0
\end{array} \right)
\]

\[
A = \left( \begin{array}{c}
G \\
\alpha I \\
\gamma D
\end{array} \right)
\]
\[ \delta m = (A^T A)^{-1} A^T \delta d \]  

(4)

Data Sample

Figure 3. Sample from field records

3. Results and Discussion

From the field records, seismic travel times are picked manually to get the observation data for the inversion. Figure 4 shows a field record picked for its first arrivals. Using intercept time and plus-minus methods, refraction travel times are interpreted to guess an initial model. A simple initial model showing a refraction plane as well as its upper and lower velocities are obtained from this analysis. The initial model can be seen in Figure 5. Furthermore, using this initial model, travel times are inverted to provide a final velocity model. An inversion is done iteratively to update the model. The final model is obtained after 100 iterations.

Figure 4. A sample of travel time picking
Using the methodology described before, velocity models for both refraction tomography and joint tomography are obtained. Figure 6 shows the comparison of the inverted models between tomography that uses only refraction wave and tomography that uses both refraction and reflection wave simultaneously. The same initial model and parameters are used to get these results. However, by utilizing two waves at a time, the inversion process uses more travel times to get the model thus there are much more additional rays that will help greatly to resolve the velocity model. Figure 7 shows the comparison of data richness or ray density belongs to each tomography method. The joint tomography scheme has denser rays propagated through the medium than that of refraction tomography. The ray is painted as white curves in the medium. The ray density explains a dramatic improvement of the given velocity model from single wave tomography to joint wave tomography. It is noticeable that the result from the joint tomography is more consistent with the geological and geophysical conditions in the site. The velocity model of joint tomography shows a nearly horizontal boundary between the upper low-velocity layer and the lower high-velocity rock. This correlates with field observation. Low velocity underlying high velocity is also confirmed from the field as the soil is much weaker than the bedrock. The upper panel in Figure 6 and Figure 7 show a causality comparison between data richness and tomogram result consecutively. The same is applied to the lower panels. The richer the traveltime data, the better the tomogram result.
Figure 6. Final velocity model comparison between refraction tomography (upper panel) and joint tomography (lower panel)

Black lines in Figure 6 are interpreted soil-rock interfaces from the inverted velocity models. The interfaces are quite distinguishable between the two given models. To analyze these results, geological reasoning is used. Groundwater flows into the lower surface. If a rock interacts more with water, it becomes weaker due to chemical weathering. The survey is run in the dry season thus water occurrence in the subsurface is unlikely, but the existing rock is a result of such interaction with groundwater in raining seasons through all the years. The refraction tomogram shown in the upper panel of Figure 6 does not agree with this reasoning and even showing a contradictory interpretation. However, the joint tomogram shown in the lower panel agrees with such reasoning.

From the result shown by the lower panel of Figure 6, it can be noticed that the bedrock located in the middle part of the survey line is weaker than that of the left and right sides. Further, this can be interpreted that in the rainy season when meteoric water infiltrates the topsoil and is blocked by the impermeable rock, the water is likely to accumulate into the central part and it will interact more intensely with the rock in this area. This explains the fact that the tomogram in the middle part of the survey where the top rock structure is concave, is weaker than the rock anywhere else. This geologically reasonable explanation cannot be inferred from the tomogram resulting from the refraction wave alone. Improvements can be noticed in terms of velocity model resolution, accuracy, and reliability.
4. Conclusion

Joint tomography of shallow seismic reflection and refraction is successfully tested in a geotechnical scale survey. A sequence of data analysis is applied to ensure each step is done properly. The sequence involves the initial model generation, travel time picking for refraction and reflection waves, forward modelling, and inversion. The result shows that the velocity model produced from the joint reflection-refraction tomography is more accurate, higher in resolution, and more reliable than that of refraction tomography. This is a promising result for this study of feasibility. In conclusion, joint tomography is potentially applicable for geotechnical purposes and should be tested in more challenging cases.

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