Delineating a low velocity zone using joint inversion of rayleigh-wave dispersion curve

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Abstract. Seismic methods widely used to study the shallow subsurface for different purposes. Analysis of P-wave refraction cannot uniquely determine the seismic velocities as a function of depth when there is a velocity layer \([1]\). It is situation commonly encountered in geotechnical site investigation. Utilization of Rayleigh wave dispersion can be used to determine the structure with the existence of low velocity zone. In this study, we discuss efficiency and effectiveness of a joint inversion of Rayleigh wave dispersion curve which combining the genetic algorithm and the Occam’s algorithm to delineate a low velocity zone. Numerical test is presented. The shear wave velocity and thickness errors which is the difference between the true and inverted model parameters is used to appraise the value accuracy inversion model. The result provides accurate solution models with is 2.3 % and is 13.4%. Finally, we demonstrates the joint inversion scheme to invert Rayleigh wave dispersion curve which calculated by phase-shift method from a real example data.

1. Introduction
Seismic methods widely used to study the shallow subsurface for different purposes. Analysis of P-wave refraction cannot uniquely detect the seismic velocities as a function of depth when there is a velocity layer \([1]\). It is situation commonly encountered in geotechnical site investigation. Utilization of Rayleigh wave dispersion can be used to determine the structure with the existence of low velocity zone \([2]\).

In this study, we discuss efficiency and effectiveness of joint inversion of Rayleigh wave dispersion curve which combining the genetic algorithm (GA) and the Occam’s algorithm to delineate a low velocity zone. A numerical and field tests is presented to show ability of this method.

2. Basic Concept
Genetic algorithm is a global optimization methods based on stochastic approach and search techniques that simulates the natural evolution process. The basic genetic algorithm comprises four stages, each executed using random probabilities \([3]\):

- Coding: representation of the model parameter using a binary coding scheme that results in an analog of the chromosome.
- Selection: selection pairs individual models for reproduction based on their fitness value.
• Crossover: combining two individuals which share information genetic to produce an offspring.
• Mutation: random alteration of some parameters in a certain chromosome

Occam’s algorithm is local optimization with constrained optimization technique in its iterative process. The theoretical aspects and general procedures of Occam’s algorithm is described by Lai and Rix [4].

3. Methods
We used the joint inversion, which combining GA and Occam’s algorithm in sequence, to invert a fundamental mode of Rayleigh wave dispersion curve. In this method, we firstly invert the Rayleigh wave dispersion curve using GA, running with small generation (i.e. 100 generation) to avoid cumbersome computational time in forward modeling. Next stage, we improve the shear-wave solution from GA using Occam’s algorithm to get final result. The schematic of joint inversion is outlined in Rubaiyn [5].

Accuracy of the inversion result is assessed through numerical test, by inspecting numerical errors of the inversion (which are shear velocity error and thickness error). These errors show cumulative difference between the true and inverted models. Finally, we demonstrate the joint inversion of Rayleigh wave dispersion curve from a real example data. The real dispersion curve is extracted using tau-pi transform.

4. Result and Discussion

4.1 Rayleigh waves synthetic test
The synthetic model is an earth subsurface structure with an existence of low velocity zone. This profile is characterized by four layers over a half space with a 2m thick of softer layer trapped between two stiffer layers. The profile represents a real complex subsurface structure that has been actually analysed and validated on a pavement test site in Hanan, China [6]. Model parameters of the profile are shown in Table 1. From these parameters, we calculate the experimental phase velocity at frequency range of 5 to 50 Hz using the reflection/transmissions (R/T) coefficients method established by Lai and Rix [4]. The experimental Rayleigh wave dispersion curve (blue color in Figure 1.a) shows increasing phase velocity transitions from the frequency 20 Hz to the higher frequency end, which indicates the existence of low velocity zone under the surface layer.

The joint inversion is started with single GA, which is set with eight string bits, eight populations, and 100 generations. The single GA is repeated for five times, and the results are averaged. The averaged shear-wave velocities versus depths are utilized as initial model in the Occam’s algorithm. The inversion results of the numerical test are shown in Figure 1. The experimental phase velocity and the calculated phase velocity have a good matching (Figure 1a). The inverted shear-wave profile shown in Figure 1b (red color) exhibits a good agreement to the corresponding true shear-wave profile (blue color), and more importantly the existence of low velocity zone is well imaged. The accuracy of the inversion results is confirmed by the small errors of the shear velocity error, (i.e., 2.3%) and the thickness error, , (i.e., 13.4%). These small errors indicate the effectiveness of a joint inversion of Rayleigh wave dispersion curve to estimate the shear-wave profile.

| Table 1. Earth model parameters of four layers over half-space |
|---------------------------------------------------------------|
| **Number of layers** | **S-wave Velocity** (m/s) | **P-wave Velocity** (m/s) | **Density** | **Thickness** (m) |
| 1<sup>st</sup> | 346 | 200 | 1.8 | 2 |
| 2<sup>nd</sup> | 765 | 150 | 1.8 | 2 |
| 3<sup>rd</sup> | 663 | 200 | 1.8 | 4 |
| 4<sup>th</sup> | 995 | 300 | 1.8 | 4 |
| **Half-space** | 1327 | 400 | 1.8 | ∞ |
Figure 1. Inversion result of syntetic model. a) The Rayleigh wave dispersion curves. The blue marker is experimental phase velocity and the red line is inversion phase velocity; b) The shear-wave profile. The blue line is true model and the red line is inverted model.

4.2 A real-world example

The field data were adopted from Safani (2007), which were acquired in Matsudai, Niigata Prefecture, Japan. The data were recorded using the OYO DAS-1 instrument with 24-channel land-streamer at 2 m geophone spacing, with the source of a wooden impacting vertically on the asphalt road at 10 m near-offset [2].

Figure 2. A real-world example of Safani [2]: (a) Imaging raw data; (b) $f_v$ spectrum calculated through tau-pi transform.
Figure 3. Inversion result of Figure 2(b): Comparison of observed (blue) and inverted (red) dispersion curve (above); and vertical shear-wave velocity profile.

Figure 4. Driling data acquired around the Matsudai ‘mud vulcano’ site [2].

Figure 2 shows imaging raw data and $f-v$ spectrum calculated through tau-pi transform. The picked Rayleigh wave dispersion curve (white color in Figure 2b) show small phase velocity transitions at frequency range of 15-20 Hz which indicate the existence of low velocity zone. The inversion results of Rayleigh wave dispersion curve provide a description of 1-D shear wave velocity profile which exhibits the existence of low velocity zone at depth of 2-5 m as shown in Figure 3b. The stiff layer under the low velocity layer, with shear-wave velocity of about 150 m/s, represents clay-gravel mix. The half-space with shear-wave velocity of about 275 m/s may represent the weathered bed-rock [2]. This results are significantly comparable to the drilling data of point (2) acquired around the Matsudai ‘mud vulcano’ site, as shown in Figure 4.

5. Conclusion
The joint inversion, which combines the genetic algorithm and the Occam’s algorithm in sequence, is an efficient and effective scheme to estimate shear-wave velocity profile. The good match of dispersion curves and the small values of numerical error from synthetic test show the advantage in efficiency of the inversion. Its implementation to real data provides the description of 1-D shear wave velocity profile, in which the low velocity zone under the surface layer can be well delineated and it is comparable to the drilling data.
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