Near-surface S-wave Estimation base on Inversion of Rayleigh Wave Dispersion Curve Using Genetic Algorithm

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Abstract. Multi-channel analysis of surface wave (MASW) is a suitable technique to infer shallow structure of vertical shear-wave velocity profile from seismic record data. The processing stage is focused on obtaining the reliable dispersion curves, and the final stage of the method is that to obtain the shear velocity model that can explain the observation. The genetic algorithm (GA) method, one of the global optimization approaches, has been implemented to obtain shear wave model from Rayleigh wave dispersion curve. The GA method mimics biological evolution in order to obtain the optimum solution. Application of GA method to two synthetic models for normal velocity profile and low velocity anomaly give good results indicated with small misfit. Finally, we demonstrate the GA to Rayleigh dispersion curve for real data which calculated by using phase-shift method.

1. Introduction

The shear wave velocity in the shallow subsurface is an important parameter in geotechnical site characterization and in-situ imaging can be accomplished quickly through the inversion of surface wave dispersion and its use has become very common in recent years [5]. Shear wave velocities can be derived from inverting the dispersive phase velocity of the Rayleigh wave. Near surface S-wave velocity can be determined by inverting high-frequency Rayleigh waves using a process that is called multichannel analysis of surface waves [11].

A key step in the multichannel analysis of surface waves (MASW) method is generating a reliable image of dispersion energy in the frequency-velocity domain. Its principles are based on the summation of wave-fields existing at all traces in on field record. The method includes $w-p, f-k$, and phase-shift methods that are slightly different in the way the dispersion image is constructed. The phase-shift method is known to active the highest imaging resolution for a given offset range [6]. From the image of dispersion energy, more than one velocity can be associated with a given frequency, thus define the fundamental mode, firsts-higher mode, second-higher mode and so on. Normally, the fundamental mode wave has strongest energy and its dispersion curve is picked to perform the inversion [2].

Inversion of dispersion curves calculated from Rayleigh waves is an implicit and nonlinear problem. The function has four unknown quantities; the layer thickness, density, P-wave velocity, and
S-wave velocity [10]. Several inversion techniques have been proposed to solve inversion of Rayleigh wave dispersion curve problems.

The linear approach can be considered as an acceptable and computationally-effective solution only when some robust a priori information is available and a good starting model can be thus established that is close to the real solution. In fact the main problem of the traditional approach is that the final solution intrinsically depends on the starting model and that poor or missing a priori information makes the final solution particularly weak [1]. Considering this, a global optimization approach is a method that not depend on this initial assumption. Genetic algorithm (GA) as one of global optimization methods that can overcome these limitations are particularly attractive for surface wave analysis [3].

In this work, Genetic algorithm inversion was employed to estimate vertical shear-wave velocity profile from the synthetic dispersion curves and dispersion curve of the real data which calculated by phase shift-method.

2. Methods

GA is an optimization method that mimic biological evolution in order to obtain optimum solution. Corresponding to the biological processes. The basic algorithm comprises four stages [7], each execute using random probabilities:

1. Coding: representation of model parameters as a bit string or chromosome.
2. Selection: selection of the most likely (best fitting) solutions.
3. Crossover: combining two model solutions to initiate a new chromosome.
4. Mutation: abrupt alteration of some parameters in a certain chromosome.

In the inversion, the densities and the P-wave velocities are assumed constant and then the shear-wave velocities and the thickness of the layers are parameters to be determined.

The misfit function [8] to be minimized is defined as:

$$ F = \chi^2 = \frac{\sum_{i=1}^{N} (C_{i}^{obs}(f) - C_{i}^{inv}(f))^2 W_i \sigma_{ei}^{-2}}{N - (2n - 1)} $$

(1)

where $N$ is the number of observed frequency points; $C_{i}^{obs}(f)$ is observed wave phase velocity dispersion curves; $C_{i}^{inv}(f)$ is theoretical phase velocity dispersion curves calculated using the reflection/transmission (R/T) coefficients method established by Lai and Rix (1998), $W$ is a weight factor; $\sigma_{e}$ are element of the data uncertainties vector, and $n$ is the number of layers of the models. To appraise the value accuracy inversion model, we used numerical error defined as [3]:

$$ E_{Vs} = \sqrt{\frac{\sum_{i=1}^{M} (V_{S_{i}}^{true} - V_{S_{i}}^{inv})^2}{\sum_{i=1}^{M} (V_{S_{i}}^{true})^2}} \times 100\% $$

$$ E_{H} = \sqrt{\frac{\sum_{i=1}^{M} (H_{i}^{true} - H_{i}^{inv})^2}{\sum_{i=1}^{M} (H_{i}^{true})^2}} \times 100\% $$

(2)

where $V_{S_{i}}^{true}$ and $V_{S_{i}}^{inv}$ represent the true and the inverted S-wave velocities of the layer respectively, $H_{i}^{true}$ and $H_{i}^{inv}$ represent the true and the inverted thickness of the layer respectively and $M$ is the number of S-wave velocities.

3. Results and Discussion

3.1. Rayleigh waves synthetic test

Two synthetic earth models are used to simulate situation commonly encountered in shallow geotechnical site characterization as shown in Table 1 and Table 2. Profile 1 consists of two layers over the half space with downwardly increasing velocity values at each layer. Profile 2 consists of four layers over half space with low velocity anomaly. The low velocity anomaly is represented by the
lowest value of shear-wave velocity (Vs) and it is located beneath the first layer. This profile is a real complex subsurface structure actually analysed and validate on a pavement test site in Hanan, China, which is adopted from Song et al. (2008).

Table 1 Earth parameter of the test Profile 1

| Number of layers | S-wave Velocity | P-wave Velocity | Density $\rho$ (g/cm$^3$) | Thickness (m) |
|------------------|-----------------|-----------------|--------------------------|--------------|
| 1$^{st}$         | 400             | 200             | 1.7                      | 3            |
| 2$^{nd}$         | 600             | 300             | 1.8                      | 5            |
| Half-space       | 800             | 400             | 1.8                      | $\infty$     |

Table 2 Earth parameter of the test Profile 2

| Number of layers | S-wave Velocity | P-wave Velocity | Density $\rho$ (g/cm$^3$) | Thickness (m) |
|------------------|-----------------|-----------------|--------------------------|--------------|
| 1$^{st}$         | 346             | 200             | 1.8                      | 2            |
| 2$^{nd}$         | 765             | 150             | 1.8                      | 2            |
| 3$^{rd}$         | 663             | 200             | 1.8                      | 4            |
| 4$^{th}$         | 995             | 300             | 1.8                      | 4            |
| Half-space       | 1327            | 400             | 1.8                      | $\infty$     |

A population size of 8 was run for 300 generation with the 8-string bit every parameters. The crossover and the mutation probabilities are all set up at 0.2. Inversion results of synthetic models illustrated in Figure 1. The left panel is result from profile-1 and the right panel is result from profile-2. As shown in Figure 1, the best model of the model population (indicated by red line) in agreement with the true velocity profiles (blue line). The accuracy of inversion results is analyzed by its misfit value and estimated parameter error. The misfit value for profile-1 is 0.59 m/s with $E_{Vs}$ is 2.1 % and $E_H$ is 15.0 % and for profile-2 is 1.48 m/s with $E_{Vs}$ is 4.4 % and $E_H$ is 8.2 %. This result show that the GA method can provide excellent estimation of shear-wave velocity profile.

Figure 1. Result from inversion of synthetic models. Rayleigh wave dispersion curve (above) and shear-wave velocity profiles where the blue line is true model and the red line is
3.2. A real-world example

The raw data is the refraction data which acquired within Institut Teknologi Bandung campus area. Hammer was used as the energy source. Twenty-four geophone was used with 1m interval, the nearest offset is 2m, and the sampling rate 1ms. The raw data is shown in Figure 2(a). The dispersion curve of Rayleigh-wave phase velocities has been extracted using phase-shift method with frequency ranging for 5 to 50 Hz as shown in Figure 2(b). The final stage is that to obtain the shear velocity model that can explain the observation.

The refraction analysis was used to estimate the number of layers, Vp and density. The a priori information from refraction analysis was used to determine the parameter ranges (Vs and H search limits). The population size of 8 was run for 300 generation with the 8-string bit every parameters. The resulted best model of 1-D shear wave profile is shown in Figure 3. Based on this result, the range of shear wave velocity is 150 m/s at the surface to 315 m/s at the 25 m depth. The inversion results of Rayleigh phase velocity dispersion curve show a good matching between the observed and inversion phase velocity dispersion curve (Figure 3.a.) indicated with small misfit (0.7 m/s).

4. Conclusions

The genetic algorithm approach is effective to estimate the shear-wave velocity profile from Rayleigh wave phase velocity dispersion curve. From the synthetic simulation, surface wave method be able to delineate the structure with existence of low velocity zone. Its implementation to the real data, of 5 to 50 Hz, provide a description of 1-D shear wave velocity profile with increasing value from the top to the 25 m depth.
Acknowledgements
We would like to thank the Department of Geophysical Engineering, Institut Teknologi Bandung for the data acquisition. We would also like to thank the participants in acquisition of the seismic data.

References
[1] Dal Moro G, Pipan M and Gabrielli P 2007 Rayleigh wave dispersion curve inversion via genetic algorithms and marginal posterior probability density estimation. Journal of Applied Geophysics 61 39-55.
[2] Gong T, Liu M, Zhang H, Li X, Chen H, Liu J, Liu R, and Ye Y 2013 Near-surface structure estimation using Rayleigh wave and a genetic algorithm 1st NSGAPC p 249-252 expanded abstracts
[3] Hamimu L, 2011 Inversion of surface wave phase velocity using new genetic technique for geotechnical site investigation University of Sains Malaysia p 15-93
[4] Lai C G and Rix G J 1998 Simultaneous inversion of Rayleigh phase velocity and attenuation for near-surface site characterization Research Report National Science Foundation and U.S. Geological Survey Georgia Institute of Technology
[5] O’ Neill A, Deinth M and List R 2003 Full-waveform P-SV reflectivity inversion of surface waves for shallow engineering applications Explorations Geophysics 34 158-173
[6] Park C B 2002 Imaging dispersion of MASW data-full vs selective offset scheme Journal of environmental and engineering geophysics 16 12-23
[7] Sen M K and Stoffa P L 1995 Global optimization methods in geophysical inversion Elsevier p 125-244
[8] Socco L V and Boiero D 2007 improved monte carlo inversion of surface wave data Geophysical Prospecting 56 357-371
[9] Song X, Gu h, Zhang X and Liu J 2008 Pattern search algorithm for nonlinear inversion of high-frequency Rayleigh-wave dispersion curves Computers and geosciences 34 611-624
[10] Xia J, Miller R D and Park C B 1999 Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves Geophysics 64 691-700
[11] Xia J, Miller R D, Park C B, Ivanov J, Tian G, and Chen C 2004 Utilization of high frequency Rayleigh waves in near surface geophysics The leading Edge 23 753-759