Shear velocity inversion from ambient seismic noise using RR-PSO: a case study of Nusa Tenggara Island

A Farduwin¹ and T Yudistira²
¹Geophysical Engineering, Institut Teknologi Sumatera
Jl. Terusan Ryacudu, Lampung Selatan 35365, Indonesia
²Global Geophysics Group, Institut Teknologi Bandung
Jl. Ganesha 10, Bandung 40132, Indonesia
E-mail: alhada.farduwin@tg.itera.ac.id

Abstract. Ridge regression particle swarm optimization (RR-PSO) is an optimization technique based on the simulation of social behavior of some animal swarm that has been successfully used in many different engineering fields. In this study, RR-PSO was used to invert Rayleigh wave phase velocity curves that extracted from ambient seismic noise records to obtain the shear velocity (Vs) profile. The optimization algorithm is relatively faster, stable and the important aspect is that can provide uncertainty information of the inversion results. In order to determine the capabilities of the RR-PSO algorithm, the synthetic simulation was carried out using both noise-free and noise-contaminated data. The validity test includes the calculation of similarity index and estimation of the model uncertainty using their standard deviation. Based on the resulted model, the convergence of RR-PSO algorithm is relatively faster, stable and adaptable to some level of noise and can provide good model estimation of the subsurface. The application of RR-PSO to the real dispersion curve data is carried out in order to determine the seismic crustal structure beneath Nusa Tenggara islands.

1. Introduction
Shear wave velocity (Vs) is an important parameter to determine earth/rock structure. In geophysical studies, this parameter used to characterize subsurface structure that can be estimated using Rayleigh wave dispersion analysis. But inferring Vs profile using Rayleigh wave dispersion curve still becomes a classic geophysical inverse problem. In this study, we used RR-PSO algorithm to obtain Vs profile from Rayleigh wave dispersion curve. This algorithm was chosen because relatively faster in data processing, stable, easily implemented and also provide uncertainty model.

In order to obtain Rayleigh wave dispersion curve, we can extract from ambient seismic noise data. Ambient seismic noise has been widely used to obtain Vs structure [1-3]. This method uses the wave field of continuous natural sources, and is more efficient and logistically less expensive compared to active source seismology. We utilized the data from 30 BMKG observation stations spread across eastern part of East Java, Bali, West Nusa Tenggara, East Nusa Tenggara and southern part of Sulawesi with a record period between January and December 2016 (figure 1). Then we used vertical data component because the Rayleigh wave more sensitive at this component. Thus, the main objective of this study is to determine shear wave velocity structure around Nusa Tenggara Islands from Rayleigh wave dispersion curve using RR-PSO inversion method.
2. Ambient Seismic Noise
The ambient seismic noise is excited by oceanic gravity waves primarily. Based on its frequency range, ambient noise is classified into several categories: seismic hum (1–20 mHz), primary microseisms (0.02–0.1 Hz), and secondary microseisms (0.1–1 Hz) [4]. To obtain dispersion curve from ambient noise, firstly we extract the Green’s function between two seismic stations using cross-correlation process. This process will produce the Empirical Green Function (EGF) which has similarities with surface wave [5] which contain of wave propagate information in layered medium between two seismic stations [6]. This process commonly called as seismic interferometry. This method has been applied in passive seismic method.

3. RR-PSO Algorithm
*Ridge regression particle swarm optimization* (RR-PSO) is an optimization technique based on the simulation of social behavior of some animal swarm that has been successfully used in many different engineering fields. RR-PSO is one of PSO family which is derived from the damped mass-spring system using finite difference [7]. In other words, this algorithm is developed by backward finite difference scheme for velocity and acceleration in that system. Mathematically, RR-PSO algorithm can be written as:

$$v(t - \Delta t) = \frac{v(t) + \phi_1 \Delta t (g(t) - x(t)) + \phi_2 \Delta t (x(t) - x(t))}{1 + (1 - \omega) \Delta t + \phi_\Delta t^2}$$ \hspace{1cm} (1)

$$x(t + \Delta t) = x(t) + v(t + \Delta t) \Delta t; \ t, \Delta t \in \mathbb{R}$$ \hspace{1cm} (2)

where $v$ is vector velocity of particles or individuals, $x$ vector position of particles or individuals, $g$ global position on the whole swarm, $\phi_1, \phi_2$ global and local acceleration constants, $\omega$ inertia weight. In geophysics, particles or individuals are the parameters sought. Those parameters are shear wave velocity ($V_s$) and thickness of layer ($H$).

4. Method
In this study, we extract dispersion curve from Rayleigh group velocity map resulted from ambient noise tomography with periods ranging from 5-35 s. From this extraction process we obtain 35 grid points.
along Nusa Tenggara Islands. Then we inverse those dispersion curve using RR-PSO algorithm with forward model using *Fast Generalized Reflection Transmission (FGRT)* method developed by [8] to obtain Vs to depth profile. This forward function has been used by [9, 10]. We use constant value of $\omega = 0.8; \phi_1 = 2; \text{ and } \phi_2 = 1.8$ [11]. We estimate $Vp$ and density ($\rho$) using empirical equation derived by [12].

$$V_p = 0.9409 + 2.0947V_s - 0.8206V_s^2 + 0.2683V_s^3 + 0.0251V_s^4$$

$$\rho = 1.6612V_p - 0.4721V_p^2 + 0.0671V_p^3 - 0.0043V_p^4 + 0.000106V_p^5$$

where $Vp$ in km/s and $\rho$ in gr/cm$^3$. Before we inverse at real data, we try to inverse at synthetic data to know how this algorithm works. Then we inverse using this algorithm at the real data.

5. Result and Discussion

In order to know the stability and robustness of RR-PSO, we test the inversion method using RR-PSO algorithm in noise-free and noise-contaminated data. We make synthetic data using 6-layers, so this algorithm has to find 11 model parameters ($V_s1$-$V_s6$ and $H_1$-$H_6$) and their uncertainty. Figure 2 shows synthetic models with 6-layer. We set the thickness parameters of $H_1 = 3$ km, $H_2 = 5$ km, $H_3 = 6$ km, $H_4 = 5$ km, $H_5 = 5.5$ km and $H_6 = \infty$ (half space). Whereas for the shear wave velocity parameters $V_{s1} = 2.8$ km/s, $V_{s2} = 3.4$ km/s, $V_{s3} = 4.0$ km/s, $V_{s4} = 2.7$ km/s, $V_{s5} = 3.3$ km/s, and $V_{s6} = 3.8$ km/s. Then for the inversion process we set 30 times iteration and use 100 particles.

![Synthetic Model](image)

**Figure 2.** (a) Synthetic model using 6-layers (b) Rayleigh dispersion curve response noise-free data and (c) 5% noise-contaminated data.
Figure 3 and 4, inversion result using RR-PSO algorithm shows good correlation, stable and robust in noise-contaminated data. In order to determine the best solution can be using mean, median, and modus. Based on statistical research [13, 14] using mean value the presence of outliers data caused the best solution keep away from true solution. If we use mood value, the data involved becomes small and not all data has a mood value. But if we use median value, the data is not affected by outlier’s data. So, using median produces the solution that approaches the true value.

Figure 3. Inversion result of noise-free data (a) Rayleigh dispersion curve response (b) earth stratigraphy model.

Figure 4. Inversion result of noise-contaminated data (a) Rayleigh dispersion curve response (b) earth stratigraphy model.

Figure 5 shows that RR-PSO algorithm is very fast to initial convergence during the first 10 iteration and using median value has the same error value with error minimum. To know the robustness of RR-PSO, we calculated the similarity index (SI) using [15]. We obtain SI value of noise-free data about 93.55% and for noise-contaminated data about 92.71%.
Figure 5. RMS error curve for various types of guesses (a) noise-free data (b) noise-contaminated 5%. Black line rms error using mean, red line rms error using median and magenta line rms error using error minimum.

From the inversion results in figure 6 and 7, performs an accurate result. This can be seen in the observation curve fitting with a fit calculation curve. The RMS error curve also looks small (figure 8). Figure 6, grid point 34 located in the sea north of Bima City and north of Sangeang Island. Very low velocity ~ 2 km/s at a depth of ~ 2.6-10 km. This low velocity is associated with the Flores back arc thrust zone. Then the velocity rises dramatically to ~ 3.2 - 3.6 km/s at a depth of ~ 10-22 km. At depths of ~ 22-27 km the velocity drops again to ~ 3 km/s. This velocity is considered as the transition velocity between the crust and the upper mantle. This is also consistent with the research conducted by [16] which gives results that the thickness of the crust on Sumbawa Island is ~ 28 km.

Figure 6. Inversion result at grid point 34 (a) dispersion curve for observed (blue line) and calculated (red line) data (b) stratigraphy model.

Figure 7, grid point 62 located in the north of Rote Island in the Savu Sea. However, there are discrepancies in the 11-12s period caused by noise contaminated observation data. Vs high velocity 4.9 km/s at a depth of ~ 2.7-10 km. This high velocity is caused by the removal of the hard bottom during
the collision process and approaching the surface. Furthermore, at a depth of ~ 10-16 km the velocity drops dramatically to ~ 3 km/s, and experiences a slight increase to ~ 3.5 km/s at a depth of 16-23 km. Very low velocity ~ 2.3 km/s found at depths of 23-29 km. This velocity is associated with the crust and upper mantle transition zones. The velocity rises to ~ 4.2 km/s at depths > 29 km which reflects the velocity in the upper mantle zone. These results also provide the same results with research conducted by [16] which concluded the thickness of the crust in the area around the island of Timor by ~ 27 km in the area around the grid point 62. In the study [1] provides the result was that in the Savu Sea the high velocity anomaly in the middle crust was caused by the lifting process during the collision process.

Figure 7. Inversion result at grid point 62 (a) dispersion curve for observed (blue line) and calculated (red line) data (b) stratigraphy model.

Figure 8. RMS error curve (a) grid point 34 (b) grid point 62.

Figure 9 shows the mean Vs to depth profile obtained from inversion process using 35 dispersion curve data along Nusa Tenggara islands. From that profile, the velocity of Vs rises slowly at depth 3-8 km. Then between ~8-13 km, the velocity of Vs relatively stable and velocity increase at depth ~13-22 km. Between depth ~22-27 km, the velocity of Vs decrease slowly becomes ~3.5 km/s and the velocity relatively increase below ~27 km. It’s indicates that the crustal transition zone begins from ~27-30 km.
6. Conclusions
We have applied RR-PSO algorithm to invert dispersion curve produced from Rayleigh group velocity map. This algorithm is stable, robust toward noise, and fast to initial convergence. Inversion result at real data along Nusa Tenggara Island obtain good result and consistent, it is indicated by the result that support each other with previous research. Using this algorithm, we obtain the crustal thickness along Nusa Tenggara Islands ranges between ~27-30 km.

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