Inversion of rayleigh waves dispersion using quantum-behaved PSO to characterize the embankment of mud flow Dam in Sidoarjo (LUSI)

Y Widyaningrum¹*, Sungkono², and A Husein³

¹Department of Physics, Faculty of Engineering, Universitas Bangka Belitung, Bangka, Indonesia
²Department of Physics, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
³Pusat Pengendalian Lumpur Sidoarjo, Indonesia

*E-mail: yekti-widyaningrum@ubb.ac.id

Abstract. The characterization of the embankment can be done by constructing the shear wave velocity in subsurface. The investigation of near surface wave velocity using Rayleigh wave dispersion analysis is popular. This method is very fast and effective to construct the vertical wave velocity, but has no unique solution. As a result, the inverse modelling is often trapped in local optimums. Therefore, we used Quantum-behaved PSO to get the best solution (global optimum). Inversion method using Quantum-behaved PSO was performed on synthetic and field measurement data. Field data acquisition was executed at P80-81 using both active and passive surface waves methods. The inversion result of Rayleigh wave dispersion is shear wave velocity structure. Shear wave velocity imaging resulted by this method was used to characterize the embankment of mud flow dam in Sidoarjo (LUSI) and be compared to the resistivity measurement data. The subsurface structure which is constructed from the inversion of Rayleigh wave gives the same result as the resistivity.

1. Introduction
In recent years, shallow seismic site characterization using the dispersion properties of Rayleigh waves gaining an interest for researchers in geology, geophysics and geotechnics. The method has been used for identifying subsidence in Mafraq city [1], investigating road failure [2]; ground characterization at railway station [3], detecting anomalous features and fracture zones in karst terrain [4]; and liquefaction hazard assessment [5].The popularity of the method is basically caused by the fast and costly effective to be done, but giving a good result to construct the vertical shear wave velocity (Vs) [6][7]. The construction of vertical shear waves velocity for near subsurface model is commonly done by inverse modelling from Rayleigh waves dispersion curve. The inversion of Rayleigh waves dispersion curve is highly nonlinear and has no unique solution [8]. As a result, inverse modelling is often trapped in local optimums. Hence, it needs an optimization algorithm which is good to find the global optimum without being trapped in local optimums.

Quantum-behaved Particle Swarm Optimization algorithm, also called QPSO is one of optimization methods which based on quantum principle and PSO algorithm which has solution in searching principle for optimization problem, like a group of animals searching for meal or avoiding the predators. Part of QPSO algorithm is adopted from quantum representation that allows representation of superposition
from all potential solutions in the given problem [9]. QPSO gives optimum strategy to differentiate the population and increases the performances of QPSO in order to avoid to be trapped in the local minimum [10][11]. QPSO is good algorithm and has been used widely to solve optimization problem [11]. The application of QPSO is in various fields such as in antenna design [10] and communication networks [12], biomedicine [13], and modelling [14]. However, in geophysical modelling, QPSO have not been applied. Geophysical modelling, especially geophysical inverse problem is non-linear and the solution must be unique because the solution represents subsurface condition. Therefore, this study is focusing on the application of QPSO algorithm to solve geophysical inverse problem, especially inversion of Rayleigh wave dispersion. The application of QPSO is used to construct the vertical shear waves velocity profile of the subsurface of LUSI embankment. The characterization of LUSI embankment is needed to monitor the condition of the embankment, since LUSI embankment has an important role to prevent the mud flowing to the residential area.

2. Research Method

2.1. Testing Quantum-behaved PSO

In order to test the performance of QPSO algorithm for geophysical data modelling, we made synthetic model that contains a four-layered subsurface with stiff layer lies between two soft layers which represents one of subsurface conditions. The synthetic model was used to estimate synthetic data by forward modelling using Fast Generate Reflection-Transmission (FGRT). Then, the synthetic dispersion data was inverted using QPSO to obtain inverted model. The performance of QPSO showed by comparing synthetic models to the inverted models.

2.2. Acquisition Field Data

Field measurement data was acquired from the measurement at point 80 to 81, written as P80-81 at LUSI embankment using both active and passive surface waves methods. However, both methods used the same linear array since it was the most suitable array to be deployed at the embankment.

2.3. Applied Quantum-behaved PSO on to Field Measurement Data

The tested QPSO algorithm then applied on field measurement data to characterize the subsurface based on shear wave velocity profile. However, before applying QPSO, fields measurement data need to be processed to estimate Rayleigh wave dispersion curve. The recorded data (i.e field data from active and passive seismic acquisition methods) were processed by the following order: active and passive seismic field acquisition data were processed using f-k transformation and SPAC, respectively to obtain dispersion energy spectra; picking the energy for active and passive seismic data from dispersion energy spectra; constructing Rayleigh wave dispersion curve by combining both active and passive seismic picking result. Hereinafter, applying QPSO on to field data to estimate shear wave velocity. Detailed QPSO algorithm has been explained by Sun [15] [16]

- Initialization of the particle is done by random using the same probability distribution function
- Particle wave function at iteration t+1 follow

\[ \psi(\chi_{i}^{t+1}) = \frac{1}{\sqrt{L_{ij}}^t} \exp \left( -\frac{|\chi_{i}^{t+1} - p_{ij}^t|}{L_{ij}^t} \right) \] (1)

where \( \chi_{i}^{t+1} \) represents the earth model that is thickness and shear wave velocity (Vs), \( p_{ij}^t \) represents the best value of thickness and shear wave in the swarm, \( C_{i}^t \) represents the average change of thickness and shear wave velocity (Vs) and \( L_{ij}^t \) represents parameter which has value of

\[ L_{ij}^t = 2\alpha|x_{ij}^{t+1} - C_{ij}^t| \] (2)

the probability density function follow

\[ |\psi(\chi_{i}^{t+1})|^2 = \frac{1}{L_{ij}^t} \exp(-2|x_{ij}^{t+1} - p_{ij}^t|/L_{ij}^t) \] (3)
and the probability distribution function follow

\[ F(X_{ij}^{t+1}) = 1 - \exp(-2|X_{ij}^{t+1} - p_{ij}^t|/L_{ij}) \]  \hspace{1cm} (4)

- Mbest (mean best) position of the particle can be calculated by the equation

\[ C^t = m_{best} = \frac{1}{M} \sum_{i=1}^{M} P_i = \left( \frac{1}{M} \sum_{i=1}^{M} P_{i1}, \frac{1}{M} \sum_{i=1}^{M} P_{i2}, \ldots, \frac{1}{M} \sum_{i=1}^{M} P_{id} \right) \]  \hspace{1cm} (5)

where M is total number of particles and \( P_i \) is personal best (Pbest) in each iteration. Therefore, the position of the particle can be updated by the equation

\[ X_{ij}^{t+1} = p_{ij}^t \pm \frac{1}{2} L_{ij} \ln(1/u_{ij}^{t+1}) \]  \hspace{1cm} (6)

where \( \alpha \) is the contraction-expansion coefficient which the value can be determined by calculating the equation

\[ \alpha = (1.0 - 0.5) \times \left( \frac{(MAXITEM-t)}{MAXITEM} \right) + 0.5 \]  \hspace{1cm} (7)

MAXITEM is the number of maximum iteration and \( t \) is the number of ongoing iterations.

3. Result and Discussion

3.1. Inversion of Synthetic Seismic Data.

The results of inversion process on synthetic model using QPSO shows in the Table 1.

| Model Parameters | Search Space | True Model (m/s) | Best Inverted (m/s) | Relative Error (%) | Standard Deviation |
|------------------|--------------|-----------------|--------------------|--------------------|-------------------|
| Vs 1 (m/s)       | 70-300       | 150             | 150,43             | 0.0028             | 0.30              |
| Vs 2 (m/s)       | 100-400      | 250             | 250,23             | 0.0099             | 0.16              |
| Vs 3 (m/s)       | 100-600      | 200             | 198,36             | 0.0082             | 1.16              |
| Vs 4 (m/s)       | 200-600      | 400             | 402,76             | 0.0069             | 1.95              |
| H 1 (m)          | 1-3          | 2               | 2.03               | 0.0150             | 0.02              |
| H 2 (m)          | 2-6          | 4               | 4.23               | 0.0575             | 0.16              |
| H 3 (m)          | 3-9          | 6               | 5.74               | 0.0433             | 0.18              |

The QPSO inversion test result on synthetic data has shown in Table 1 and Figure 1. Rayleigh waves dispersion curve fitting between observed phase velocities (purple circle in Figure 1a) and modelled dispersion curve (solid blue line in Figure 1a) shows the curve is almost perfectly fit. The relative error of every model parameter between the true model and model estimated by QPSO inversion is less than 0.06% and the standard deviation is no more than 1.95. This means QPSO algorithm is robust and the solution is acceptable.
3.2 Inversion of Seismic Field Data

Inversion results of data acquisition at P80-81 LUSI embankment shows in Figure 2.

Figure 2. Subsurface profile of P80-81 LUSI embankment. a) Rayleigh wave dispersion curve; b) 1-D Shear wave velocity model
Since QPSO algorithm shows a good result on synthetic data, we applied the algorithm to the field data acquired at P80-81 LUSI embankment. In Figure 2a, the extreme misfit of Rayleigh wave dispersion curve between the observed phase velocities (purple circle) and modeled phase velocities (blue solid line) is happened at frequency 5-15 Hz. This is likely caused by the inclusion of noise in surface wave data. At higher frequency 15-30 Hz, Rayleigh wave dispersion curve fitting is reasonably well. It relatively has same phase velocity value, between 200-250 m/s.

Then, starting at frequency 20 to 5 Hz, Phase velocity of Rayleigh wave continuously decreases. However, since then, shear wave velocity value increase significantly, reaching more than 250 m/s. At this point, Rayleigh waves dispersion has characteristic that the lower frequency, the higher its phase velocity. This has another meaning that the greater of the depth, the faster phase velocity.

Figure 3 and 4 show 2-D resistivity cross section at P79-82 and 2-D Shear wave velocity profile at P80-81 at LUSI embankment, respectively. On both figures, the first 12 m depth is the LUSI embankment, bordered by the pink dashed line. In resistivity cross section (Figure 3), the surface wave acquisition is starting from point 110 until 155 (shown by black arrow, from the left to the right). On both figures, we can clearly see that the subsurface of the embankment body has different properties than the subsurface below the embankment body. The embankment body has resistivity value varying between 2.2-29.2 Ohm-m (Figure 3) and shear waves velocity value varies from 220-260 m/s (Figure 4). While under the embankment, the resistivity value varies from 0.16 to 1.4 Ohm-m and shear waves velocity value varying between 40-240 m/s. The higher resistivity or shear waves velocity value means the subsurface characteristic is getting denser and vice versa. This means the subsurface characteristic of LUSI embankment body at P80-8 is denser than the subsurface below the embankment.

![Figure 3. 2-D Resistivity cross section at P79-82 LUSI Embankment][17]

![Figure 4. 2-D Shear wave velocity profile at P80-81 LUSI Embankment][17]
4. Conclusion

The inversion of Rayleigh waves dispersion using QPSO on synthetic and field data show trustable result. The characteristic of LUSI embankment that constructed from the inversion process give the same result as the resistivity measurement data.

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