Alternative surface wave analysis method for 2D near-surface imaging using particle swarm optimization

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Main objectives. The main objective is to develop an alternative two-dimensional imaging method using Rayleigh surface wave dispersion analysis.

New aspects covered. surface wave analysis; two-dimensional imaging; global optimization; swarm intelligence;

Type of presentation. Prefer poster but accept oral

Topic. 01 New Technologies in Applied Geophysics

Summary. The shear-wave velocity is one of the parameters of interest for the geotechnical design of wind turbine foundations. Near-surface seismic parameters are generally inferred using surface wave analysis, *i.e.*, effective Rayleigh dispersion curve inversion. However, in offshore context near southern Bretagne (France), where geologic structures are complex, the planar stratified media (1D) hypothesis can not be used, and recently developed full waveform inversion declinations for near-surface imaging are difficult to implement at the scale of civil engineering (number of shots, receivers, almost perfect knowledge of the source waveform and repeatability). In this context, this work aims to develop an alternative two-dimensional imaging approach based on particle swarm optimization and a sparse spatial discretization of the medium to obtain smooth parameter models. Exploiting the complete dispersion diagrams instead of dispersion curve only, the preliminary results show that swarm intelligence based algorithm allows to assess physical parameters (S-wave velocity) and lateral variation.

Introduction

In the current context of the development of offshore windfarms, the geotechnical apprehension of the seabed is crucial. Regarding the development of offshore wind turbines, one of the key issue lies in the qualification of the near-surface mechanical parameters and their spatial variability. The shear-wave velocity (S-waves) is one of the parameters of interest for the geotechnical design of foundations (Kaynia, 2011). Thus, the evolution of marine seismic measurements and their exploitation, classically processed with body waves, towards methodologies of surface waves analysis has been proposed in North Sea by Socco et al. (2011).

However, in some areas such as the 20 nautical miles in southern Bretagne (France), the coastal near-surface media has significant structural complexity. Thus, in the contexts of the French west coast, where the planar stratified media (1D) hypothesis can no longer be followed, seismic methods based on the analysis of the surface waves dispersion reach their limit of validity. To face this issue, the approach proposed here, included in the WeaMEC PROSE regional project aims to define the feasibility of imaging techniques for the geology of underwater sediments from seismic techniques using surface waves adapted to the recognition of environments with high spatial variability.

For this type of context, the potentialities of the full waveform inversion (FWI) demonstrated in terrestrial environments by the recent consideration of surface waves (Masoni et al., 2014; Pérez Solano et al., 2014) on complex structures open up possibilities for the recognition of shallow marine near-surface when structures have lateral variability. However, the effectiveness of full waveform approaches depends strongly on the fine spatial data sampling, the regular soil-receiver coupling as well as the repeatability of the source and its frequency adequacy at the scale of the desired structures, *i.e.*, on a sufficiently wide range to overcome the problems of phase ambiguities at low frequencies while integrating sufficiently high frequencies to solve the finer scales. Moreover, knowing a smoothed version of the medium to define an initial model is crucial for waveform inversion methods based on local optimization. For these reasons, we propose here an alternative inversion method, by global optimization of the problem, based on the particle swarm optimization method (PSO) and on a sparse discretization of the medium to reduce the computation cost.

For that, the study proposed here involves an innovative workflow included three major processing approaches: the PSO processing tool, a sparse spatial sampling of the model, the dispersion diagram as the data to be inverted. After summerizing the PSO principle below, a numerical test applied to a 2D model typical of complex offshore media is presented to estimate the potential of this alternative.

Methodology

The approaches based on local optimization are strongly dependent on the initial model (strong *a priori*). Several alternative approaches based on global optimization methods make possible to overcome this constraint, for example: the Monte-Carlo method, simulated annealing or genetic algorithms. Among these global optimization methods, Particle Swarm Optimization (PSO), proposed by Eberhart and Kennedy (1995) and recently introduced in geophysics by Shaw and Srivastava (2007) and Yuan et al. (2009), stands out because of its efficiency, its ease of implementation and its reduced number of control parameters.

In PSO, the first step is to randomly generate a population of n particles in the defined solution space. Each particle is defined by a position vector x containing the parameters of the model and a velocity vector v controlling the movement of the particle. At iteration k, x and v are updated such that (Eberhart and Shi, 2000):

$$\begin{aligned} v_i^k &= \chi\left[v_i^{k-1} + r_p c_1 (x_{p,i} - x_i^{k-1}) + r_g c_2 (x_g - x_i^{k-1})\right] \\ x_i^k &= v_i^k + x_i^{k-1} \end{aligned} \tag{1}$$

where χ is the constriction factor, $x_{p,i}$ and x_g are, respectively, the best position reached by the individual and the whole swarm, r_p and r_g are random variables generated at each iteration and c_1 and c_2 are,

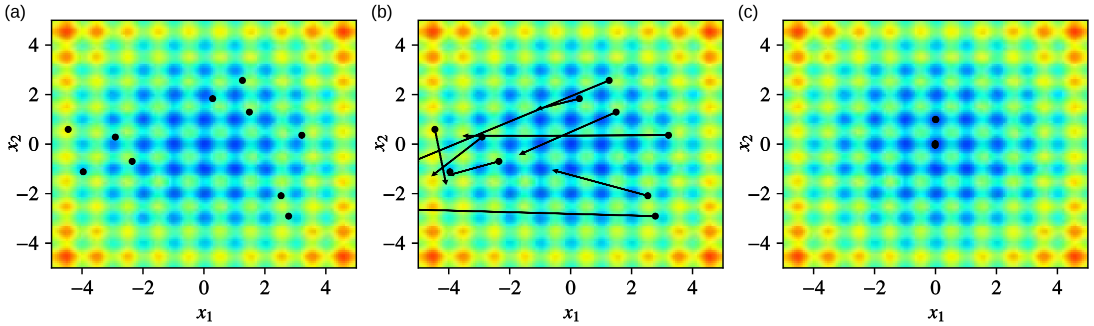

Figure 1 (a) Random drawing of the particle positions (x). (b) First update of the particle positions, the arrows represent the velocity vectors v. (c) Particle positions at the final iteration (100), several particles reached the global minimum ($x_1 = 0$; $x_2 = 0$).

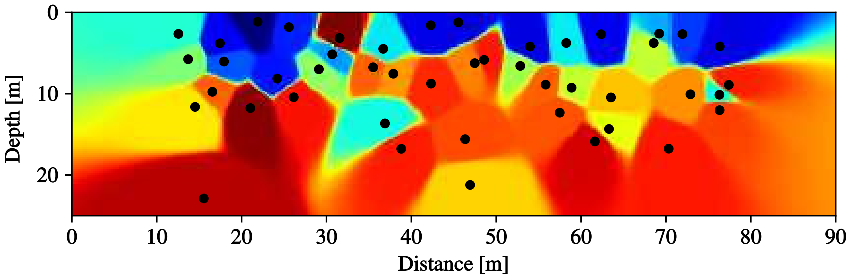

***Figure 2** Example of a velocity model reconstructed by interpolation from randomly generated points.*

respectively, the cognitive and the social parameters.

PSO is controlled by four parameters: the number of particles, the number of iterations and the parameters c1 and c2 to play on the exploitation-exploration balance (χ value depending on c_1 and c_2). Figure 1 presents a simple optimization case to find the position of the global minimum of the Rastrigin 2D function. This example uses 10 particles, 100 iterations and $c_1 = c_2 = 2.05$. At the final iteration (100), 7 of the 10 particles reached the global minimum of function.

In order to allow the reconstruction of a spatially smooth model while maintaining, in the inversion process, a limited number of unknowns, the choice was made to define the tested models only with a limited number of spatial locations for the velocity parameters assessment. Figure 2 shows an example of a randomly generated model: 50 randomly generated points are used to define the model. Each point carries five parameters: the position of the point in depth and distance (2 parameters), S-wave velocity, density and Poisson's ratio.

In order to build a 2D model from these points, an inverse distance weigthning interpolation is performed. The model thus reconstructed can be easily used for example in a finite difference modeling code.

Generally, surface wave analysis is limited to the exploitation of effective dispersion curves. However, additional information on the medium is contained in the complete dispersion diagram (Pageot et al., 2017). Thus, this last (for the Rayleigh waves) is considered here as reference data during the inversion process. Figure 3 summarize the several steps of the proposed process.

Numerical application

Synthetic data are produced using 2D finite difference time domain elastic propagation modeling code (Levander, 1988). The reference data are computed in a simple near-surface model shown in Figure 4 (a) for two symmetric acquisitions. The receiver line is centered at 45 m and consists of 48 receivers spaced of one meter. The first source is located at 10.0 m, the second at 45 m and the third at 80.0 m. A dispersion diagram is calculated for each shot.

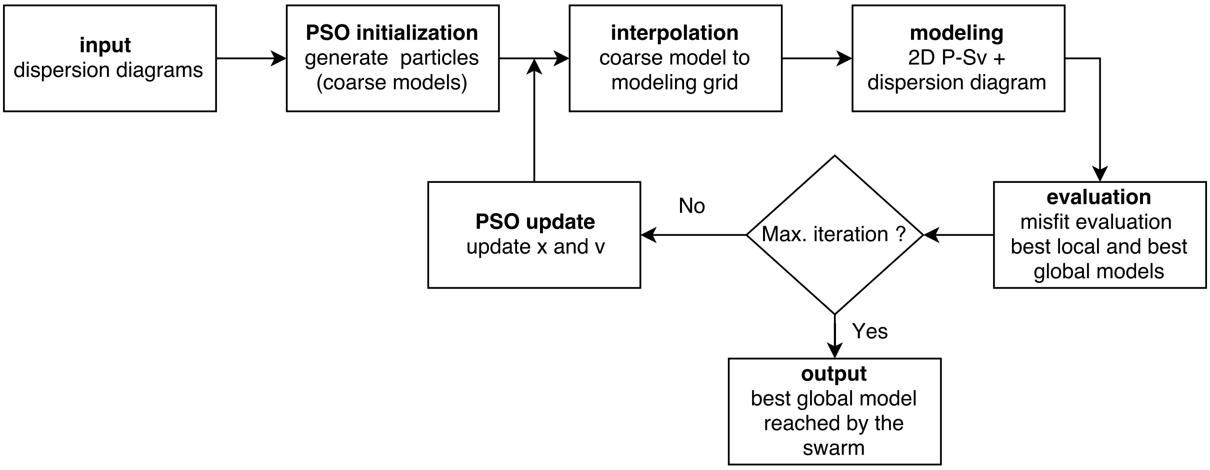

Figure 3 *Workflow of the method.*

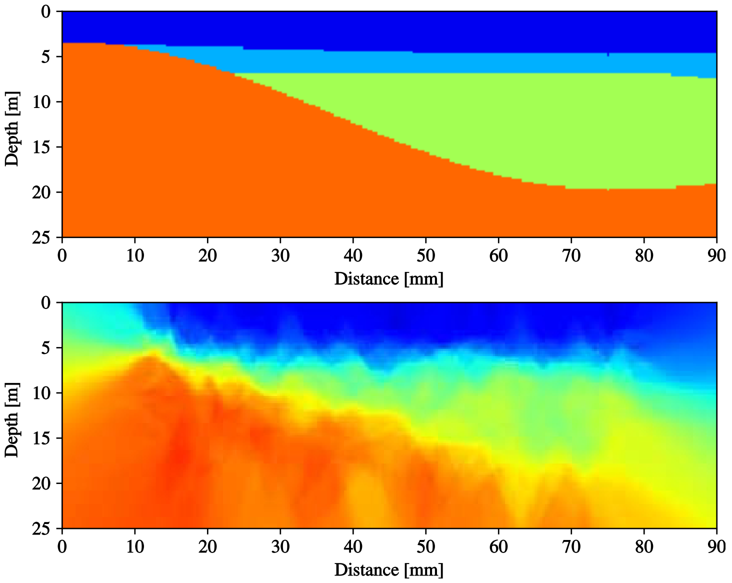

Figure 4 *(a) Synthetic S-wave velocity model used to generate the numerical data. (b) Average (all local best) inversion result using the particle swarm method and exploiting the complete dispersion diagram.*

For this inversion process, 150 models (particles) are generated randomly as described in the previous section (same distribution and positioning of points). The number of iterations is fixed at 200, the parameters c_1 and c_2 are fixed, respectively, at 2.8 and 1.3 following the recommendation of (Song et al., 2012) for the 1D case. Only the position (x, z) of the moving points and the velocities of the S-waves are sought, the density and the Poisson's ratio being fixed and constant (2000 kg / m3 and 0.35). The limits of the solution space are determined such that: $0. < z < 25\ m$, $10. < x < 80.$ and $100 < Vs < 1200.\ m/s$ for all points.

Figure 4 (b) shows the best S-wave velocity model obtained after 200 iterations. Although this smooth model is inaccurate, it has interesting characteristics: (1) a certain level of lateral variation of the medium could be reproduced, (2) the variations of vertical velocities generally respect those of the original model as presented in figure 5. In particular, the velocity and global shape of the deepest layer, *i.e.* the lateral variation, is respected.

Conclusions

Preliminary results of a new imaging method using surface waves were presented. Many points remain to be explored (parameterization of the inversion, spatial sampling of the medium, sensitivity to noise)

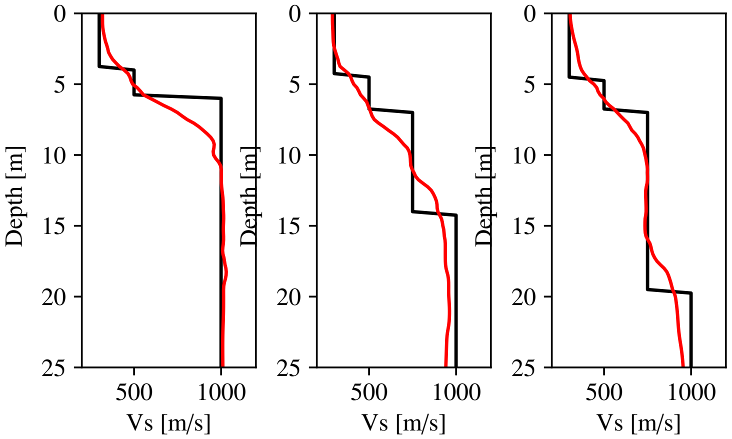

Figure 5 *Comparison of S-wave velocity in depth between the synthetic model (black lines) and the reconstructed model (red lines) at 20, 45 and 70 m.*

and to improve (taking into account the attenuation). However, this method appears promising and could provide a first step for building initial model for high-resolution imaging methods. To go further in terms of validation, experimental data from small-scale modeling will be used.

Acknowledgments

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