The 19th Iranian Geophysical Conference–November, 2020, pages 306-309

Crustal and upper mantle structures of SE Iran by combined surface wave velocity analysis and gravity modeling

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ABSTRACT

In this study, we develop and test a new Rayleigh wave dispersion curve inversion scheme using the Shuffled Complex Evolution (SCE) algorithm. The proposed inverse procedure is applied to non-linear inversion of fundamental mode Rayleigh wave group dispersion curves for shear and compressional wave velocities. At first, to determine the efficiency and stability of the SCE method, two noise-free and two noisy synthetic data sets are inverted. Then real data for Makran region in SE Iran are inverted to examine the usage and robustness of the proposed approach on real surface wave data. In a second step, we applied 3D Gravity Modeling based on surface wave analysis results to obtain the density structure and thickness of each layer. The reason for using both types of data sets, is that surface wave group velocities are good for placing layer limits at depth, but they are not very sensitive to densities. Therefore, using gravity data increases the overall resolution of density distribution. In a final step, we used again the SCE method to invert the fundamental mode Rayleigh wave group dispersion curves based on the gravity results. Gravity results like thicknesses and sediment densities have been used to constrain the limit of search space in the SCE method. Results show a high shear and compressional velocity under the Gulf of Oman which reduce to the North of the Makran region. The Moho depth of the Oman Gulf is about 18-28 km and it increases to 46–48 km under the Taftan-Bazman volcanic-arc. The density image shows an average crustal density with maximum values under the Gulf of Oman decreasing northward to the Makran.

Keywords: Rayleigh wave group velocity, Shuffled Complex Evolution, Gravity, Moho depth, Shear velocity

INTRODUCTION

The aim of this study is to calculate the seismic wave velocity variations and density structure of the crust and upper mantle in the Makran area, SE Iran. Our data are Rayleigh wave group velocity dispersion curves and gravity anomalies. In recent surveys, Rayleigh wave group velocities have been used as a tool to estimate shear and compressional wave velocities and density variation at different depths to characterize the crust and upper mantle structure. However, as is the case for most other geophysical optimization problems, inversion of Rayleigh wave dispersion curves, is typically a highly non-linear, multi-parameter, and multimodal inversion problem (Julia et al., 2000). In this work, we implemented and tested a new inversion scheme for Rayleigh wave group velocity dispersion curves based on the SCE approach. The calculation efficiency and stability of the proposed inverse procedure are tested on two synthetic models and a real data set in the Makran region, SE Iran. Surface wave dispersion curves are primarily sensitive to seismic shear wave velocities. Theoretically, the dispersion curve is a non-linear function of shear wave velocity, compressional wave velocity and density of the media and it has been proven that the sensitivity to for density is smaller than velocity. On the other hand, gravity data may be used to better constrain the density distribution. They have good lateral resolution, but bad vertical resolution. In this way, surface wave dispersion curves, which are good for placing layer limits at depth, and gravity data, which are sensitive to lateral density variations give complementary information and increase the overall resolution of crustal and upper mantle structures. Therefore, we propose here to carry out a sequential inversion of wave dispersion curves and gravity data. We expect to obtain a three-dimensional density model with well constrained discontinuities in addition to S-wave velocity distribution.

GEOLOGICAL SETTING

The 1000 km long Makran mountains (Figure.1) form the southeastern end of the Arabian–Eurasian Plate boundary, where the oceanic crust of the Arabian plate (Oman seafloor) is subducting northward beneath the Makran belt since the early Cretaceous. The E-W trending Makran is located between two, nearly N–S directed transform fault systems. To the west, the dextral Minab fault separates the Makran subduction zone from the Zagros continent–continent collision zone and to the east, the sinistral Chaman fault system separates it from the Indian continent (Figure. 1).

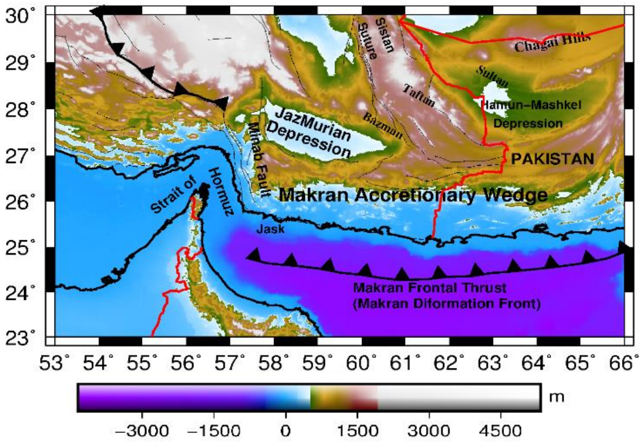

Figure. 1- Topography map of the study area, Makran (http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1).

Also, it has been found that the average range of the Moho depth increases in the Makran region from S to N. The shear-wave velocity images of the upper mantle across the Makran subduction zone depict a high-velocity anomaly under the Oman seafloor, which is subducting under the entire zone of Makran belt (Shad Manaman et al., 2011; Abdollahi et al., 2019).

DATA

Our dispersion velocity data set consists of fundamental-mode Rayleigh wave group velocities at periods of 16 s, 20 s, 24 s, 30 s and 40 s for each point on a grid of 1° by 1° in Makran between 53-66E and 23-30N (Abdetedal et al., 2015). The gravity data used for inversion come from freely accessible global free-air gravity data with a resolution of 2.5 by 2.5 arc-minutes (http://bgi.omp.obs-mip.fr).

SURFACE WAVE VELOCITY ANALYSIS BASED ON SCE METHOD

The SCE method is a metaheuristic for global optimization, proposed by Duan et al. (1992). In the SCE method, the population is divided into sub-populations, named complexes. The inversion algorithm is composed of several cycles of population optimization. At every cycle, an internal optimization mechanism, called Competitive Complex Evolution (CCE), makes evolve each complex over several iterations. After each cycle of CCE iterations, the complexes are recombined to recreate the main population. Then, new segmentation and partitioning creates new complexes and will thus shuffle the population and complexes. This algorithm is based on a synthesis of four concepts that have proved successful for global optimization: 1) Combination of deterministic and probabilistic approaches; 2) Systematic evolution of a "complex" of points spanning the parameter space, in the direction of global improvement; 3) Competitive evolution;

and 4) Complex shuffling. The synthesis of these elements makes the SCE method effective and robust, and also flexible and efficient (Duan et al., 1992; Sorooshian et al., 1993). The area of interest is subdivided into rectangular columns of constant size in E–W (X) and N–S (Y) direction. In depth (Z), each column is subdivided into four layers: sediments, upper and lower crust and mantle. In each layer and each column, we consider velocities and densities to have a linear vertical gradient. We are thus looking for the layer thickness, average P-wave and S-wave velocity, the average density ρ, as well as the vertical gradients of the three physical properties.

SYNTHETIC AND REAL DATA INVERSION BASED ON SCE METHOD

In order to show the utility of the SCE inversion for 1D Rayleigh wave dispersion curves, we applied this method to two noise-free and their corresponding noisy synthetic 1D models. As mentioned before, for noise-free synthetic data, shear wave velocities, compressional wave velocities and thickness of each layer can be fairly well resolved by the SCE algorithm. To further explore the performance of the SCE algorithm described above, Rayleigh wave dispersion curve data have been analyzed in this study using the SCE algorithm in the Makran, SE Iran. Our area is divided into a rectangular grid, with columns that have a constant size of 1° by 1° in E-W (X: 53°-66°) and N-S (Y: 23°-30°). In the vertical direction (Z), each column is divided into four layers: sediments, upper crust, lower crust and mantle. So, the total number of data, the group velocity dispersion values for the periods of 16 s, 20 s, 24 s, 30 s and 40 s for each point on the grid in Makran, is $N_U = N_{Xu} * N_{yU} = (14 * 8) * 5 = 560$. Similar to the inverse strategy of the synthetic data, we applied the SCE method also to the real data.

GRAVITY MODELING

As mentioned above, the dispersion curve is a non-linear function of shear and compressional wave velocity and density of the media. However, the sensitivity to shear and compressional wave velocity is greater than the sensitivity to the density. So, we have done gravity modeling to increase the resolution of the density model. To calculate the gravitational effect of a rectangular column with a linear vertical density variation, we used the analytical formula of Gallardo-Delgado et al. (2003). The area of interest, Makran, is also here subdivided into rectangular columns of constant size 1° by 1° in E–W (X: 53°-66°) and N–S (Y: 23°-30°) direction. In depth (Z), each column is subdivided into four layers: sediment, upper crust, lower crust and upper mantle. The distance between the gravity data points is 0.2° by 0.2°. The program minimises two terms, the relative importance of which may be controlled by the user. The first term corresponds to the data misfit and the second term to the distance of the final model from the initial model containing, if available, a priori information. Minimizing the cost function ultimately takes the following iterative form (Menke, 2012):

$$p^{k+1} = p^k + \left(G^T C_d^{-1} G + \lambda C_p^{-1}\right)^{-1} \left(G^T C_d^{-1} \Delta d\right) \qquad (1)$$

Here, Δ**d** is the vector of difference between the measured data and those calculated with model parameters $\mathbf{p^k}$ and $\mathbf{C}_d$ is the variance matrix of the data, containing on the diagonal the squared uncertainty of each data point. **p** is a vector with the model parameters, $\mathbf{p_0}$ is the vector of initial parameters and $\mathbf{C}_p$ the variance matrix of the parameters which has on its diagonal the uncertainties (variability) σ_p^2 of the parameters. *k* is the number of iterations and G is the Fréchet derivative matrix. The damping factor λ controls the overall importance of data adjustment (ε_d) with respect to distance of calculated and initial model parameters (ε_p).

REAL DATA INVERSION BASED ON SCE METHOD CONSTRAINED BY GRAVITY MODELING RESULTS

In a final step, we used the results of gravity modeling to constrain densities by performing a second round of surface wave dispersion inversion with the SCE algorithm. Finally, the Moho geometry, average crustal shear wave velocity and average crustal density for the Makran region are shown in Figure. 2.

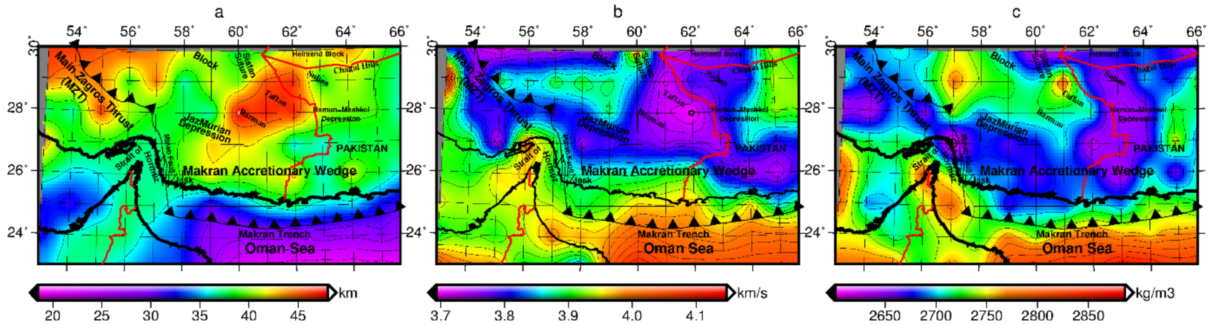

Figure 2. The final model based on the SCE inversion. a) Moho depth (km), b) average crustal shear wave velocity (km/s) and c) average crustal density (kg/m3) of Makran based on the SCE inversion.

CONCLUSIONS

We implemented a new method of iterative, sequential inversion of gravity anomaly and Rayleigh wave group velocity data. With this method, we established a model of the crust and upper mantle structure of the Makran region which is one of the largest accretionary wedges on the globe, formed by the convergence between the Eurasian and the Arabian Plates. The main results of the modeled parameters are as follows (Abdollahi et al., 2018):

1. The Oman Gulf is characterized by a Moho depth of about 18-28 km in the southern part, increasing northward towards the Iranian coast to 35 km. Further North, the Moho depth increases to 35-40 km below the JazMurian basin and 46–48 km beneath the Taftan-Bazman volcanic-arc which is compatible with earlier studies in the region.
2. The shear velocity images of the upper crust and lower crust display a high-velocity anomaly under the Gulf of Oman with an oceanic crust, decreasing northward towards the Makran region with a continental crust.
3. The density image of the region shows that the average crustal density is relatively high under the Gulf of Oman with an oceanic crust, decreasing northward to Makran with a continental crust.

REFERENCES

Abdetedal, M., Shomali, Z.H., Gheitanchi, M.R., 2015. Ambient noise surface wave tomography of the Makran subduction zone, south-east Iran: Implications for crustal and uppermost mantle structures. Earthq. Sci. 28, 235–251.

Abdollahi, S., Ardestani, V.E., Zeyen, H., Shomali, Z.H., 2018. Crustal and upper mantle structures of Makran subduction zone, SE Iran by combined surface wave velocity analysis and gravity modeling. Tectonophysics 747–748, 191–210.

Abdollahi, S., Zeyen, H., Ardestani, V.E., Shomali, Z.H., 2019. 3D joint inversion of gravity data and Rayleigh wave group velocities to resolve shear-wave velocity and density structure in the Makran subduction zone, south-east Iran. J. Asian Earth Sci. 173, 275–290.

Abdollahi, S., Ebrahimzadeh Ardestani, V., Zeyen, H., Shomali, Z.H., 2019. Imaging the crust and upper mantle structures in the Makran subduction zone in south-east of Iran. 3rd TRIGGER International Conference, Zanjan, Iran.

Duan, Q., Sorooshian, S., Gupta, V., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resour. Res. 28, 1015–1031.

Gallardo-Delgado, L.A., Pérez-Flores, M.A., Gómez-Treviño, E., 2003. A versatile algorithm for joint 3D inversion of gravity and magnetic data. Geophysics 68, 949–959.

Julia, J., Ammon, C.J., Herrmann, R.B., Correig, A.M., 2000. Joint inversion of receiver function and surface wave dispersion observations. Geophys. J. Int. 143, 99–112.

Menke, W., 2012. Geophysical Data Analysis: Discrete Inverse Theory. Academic Press, London.

Shad Manaman, N., Shomali, Z.H., Koyi, H., 2011. New constraints on upper-mantle S-velocity structure and crustal thickness of the Iranian plateau using partitioned waveform inversion. Geophys. J. Int. 184, 247–267.

Sorooshian, S., Duan, Q., Gupta, V.K., 1993. Calibration of rainfall-runoff models: Application of global optimization to the Sacramento Soil Moisture Accounting Model. Water Resour. Res. 29, 1185–1194.