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Advantages of using multiple data sets in geophysical inversion

Abstract

Besides with the inherent problem of ambiguity, the final solution of geophysical inversion for subsurface structure has a strong dependence upon prior information about the structure itself. A good starting model, based on the prior information, is an absolute necessity for successful convergence of any gradient based inversion methods. However, development of global optimization techniques like Monte Carlo method and its variants has changed the scenario to a great extent. These techniques analyze the probability of a large numbers of models to explain a set of observed data and the dependence of the final solution on the starting model gets reduced significantly. However, the importance of prior information and use of multiple data sets are still important as it helps to reduce uncertainty and leads the solution to a more geologically feasible one. Thus, use of multiple geophysical datasets is an area of consistent interest in geophysical inversion. The combination of different data sets can be done in several ways, like joint inversion, simultaneous inversion or constrained inversion. In this field of study, joint use of gravity and seismic data is always interesting due to their complimentary nature and the scope to capitalize the advantages of both. The present work is based on combined use of gravity and seismic travel time data in two different ways, joint inversion and constrained inversion. The joint inversion technique is applied on the field data collected over the Ryukyu subduction zone offshore Taiwan during an ocean bottom seismometer (OBS) experiment. The constrained inversion technique is applied to delineate the complex structure of Shilong Plateau (India) using earthquake travel time data and gravity data. The global optimization technique, Simulated Annealing, is used for optimization.

Introduction

Inversion of geophysical data is always a challenging area of study due to its dependence on initial model as well as for its inherent ambiguity. Numerous geological models can cause comparable anomalies in geophysical observation Classical methods using local properties of the objective (misfit) function to minimize, viz., the steepest descent, the conjugate gradient method or methods using the curvature information etc. pose the restrictive requirement of an initial model to be selected very close to the true model. So, to be precise, one can view the problem as that of solving for a better solution when an acceptable solution is already known beforehand. Fortunately, the development of different global optimization techniques like Monte Carlo method and its variants, viz., simulated annealing (SA), genetic algorithm (GA) etc. have reduced the dependence of initial model to a great extent. The tremendous improvement in computational speed in recent times made it possible to handle thousands of models at a time and to reach to a global solution within a reasonable time frame. However, prior information is needed to limit the model space for better convergence and speed.

On the other hand, the use of multiple data sets in geophysical inversion is, definitely, a trickier area. Integrated model generally results in a more geologically realistic solution than what is obtained by an individual analysis. Thus, to capitalize the advantages of different methods and to constrain the geological model, data from different geophysical surveys are combined to provide a more complete picture of the subsurface geology. The most popular and widely explored field of such cooperative interpretation is the combined use of gravity and seismic data. The seismic and gravity method complement each other in various ways. Gravity is a powerful method for delineation of shallow structures as its amplitude decays rapidly with depth. On the other hand, commonly employed wide-angle seismic surveys are more effective for mapping deeper structures. Further, the gravity method is sensitive to lateral variation of mass distribution only, while sharp vertical variations in structures can only be detected by seismic survey. Depending on the data quality, prior information and expected accuracy of the density-velocity relationship, integration of gravity and seismic data can be done in three different ways namely (i) Separate i.e., no coupling between density and velocity parameters and the boundaries or layer interfaces are also independent, (ii) Unified that assumes a coupling between the density and the velocity and the boundaries are also common and (iii) Mixed, is a compromise between Separate and Unified i.e., either boundaries are common with no explicit density–velocity relation or, some coupling is allowed between the density and the velocity and boundaries may also be allowed to vary a little. Strykowski (1999) precisely pointed out some technical details in the mathematical formulation for the joint seismic–gravity inversion problem. Nielsen and Jacobsen (2000) presented an integrated inversion scheme for crustal modelling by using wide-angle seismic and gravity data.

In the present study, the gravity and seismic data has been used in two different ways. The first one demonstrates a nonlinear inversion technique for joint inversion of first arrival travel-time and gravity data along two lines collected offshore Taiwan during the TAICRUST experiment conducted in 1995. The second approach is gravity constrained seismic inversion is applied on earthquake travel time data and gravity data over Shillong Plateau of Assam of north-east India. In both the cases, we employed a layer-based model description, in which interfaces (which may also be called iso-velocity/ iso-density lines) are defined by a summation of arc-tangent functions. Arc-tangent functions are highly flexible in mapping smooth interfaces as well as the sharp changes in depth of an interface. Within each layer, the velocity/ density is assumed to vary linearly with depth at each surface location. These nonlinear optimization problems are solved by the global optimization technique, very fast simulated annealing (VFSA).

Methodology

Objective Function: The main objective of our work is to combine information from seismic first arrival travel time and gravity data to obtain subsurface images that explain both the observations. Note that the travel time and gravity data are sensitive to different physical parameters, which are generally related and can be considered as outcomes of two different experiments. Let $\mathbf{T}$ and $\mathbf{g}$ represent the vectors of travel time and gravity anomalies respectively. Let $\alpha(\mathbf{x})$, and $\rho(\mathbf{x})$ represent spatial distributions of the compressional wave velocity and density respectively and $\mathbf{x}$ represent a position vector. 'obs' and 'syn' is suffix represent observed and synthetic data respectively.

For joint inversion approach, the objective or error function is represented as below

$$E(\mathbf{x}) = \left\| \mathbf{T}_{obs} - \mathbf{T}_{syn} \right\| + w \left\| \mathbf{g}_{obs} - \mathbf{g}_{syn} \right\| \qquad (1)$$

In Equation (1), the symbol $\| \; \|$ represents a suitably chosen norm and w is a weight. We use an L_2 norm such that

$$E(\mathbf{x}) = (\mathbf{T}_{obs} - \mathbf{T}_{syn})^T \mathbf{C}^{-1} (\mathbf{T}_{obs} - \mathbf{T}_{syn}) + w (\mathbf{g}_{obs} - \mathbf{g}_{syn})^T \mathbf{C}^{-1} (\mathbf{g}_{obs} - \mathbf{g}_{syn}) \qquad (2)$$

where the superscript T denotes a matrix transpose and the matrices C_T , and C_g are the data covariance matrices for travel time and gravity respectively. However, for constrained inversion, each data set get inverted separately and we use separate objective function E_1 and E_2 for seismic and gravity respectively as below

$$E_1 (\alpha (\mathbf{x})) = \|\mathbf{T}_{obs} - \mathbf{T}_{syn}\| \quad \text{and} \quad E_2 (\rho (\mathbf{x})) = \|\mathbf{T}_{obs} - \mathbf{T}_{syn}\| \qquad (3)$$

In this work, Very Fast Simulated Annealing (VFSA), which is a variant of Simulated Annealing, one of the most popular global optimization technique, is used for optimization of objective function. This method does not require any stringent starting model, as the algorithm search a very wide region of the parameter space (Sen and Stoffa, 1995).

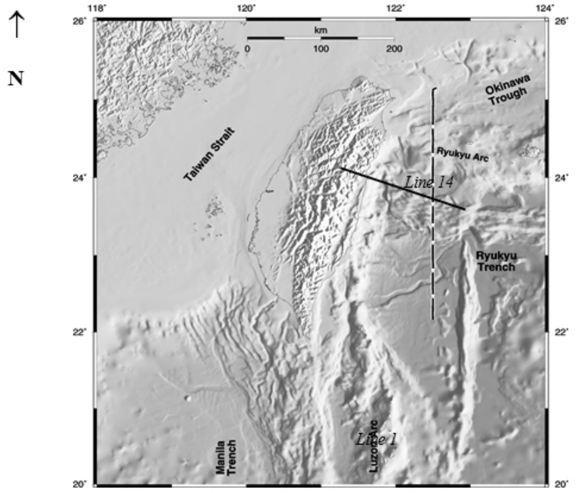
Model parameterization: We define our model space such that they consist of a few distinct layers. We allow for tremendous flexibility in the definition of our interfaces which are essentially iso-velocity/density lines. We define an interface in 2D using a sum of arc-tangent functions in horizontal distance *x* (Figure 1a), such that

$$z(x) = z_0 + \sum_{k=1}^{n} \Delta z_k \left(0.5 + \frac{1}{\pi}\tan^{-1}\left(\frac{x - x_k}{b_k}\right)\right), \qquad (4)$$

where z is the depth, n is the number of arc-tangent nodes, z_0 is an average depth of the interface, x_k is the horizontal location of an arc-tangent node, and Δz_k is the vertical throw attained asymptotically over a horizontal distance of b_k . The entire model space is defined by a set of such interfaces. In addition to searching for the arc-tangent parameters, we also search for the velocities above and below each interface.

Results

Example 1: Joint inversion of seismic first arrival travel time and gravity data: The application of the proposed technique is applied to a field dataset consisting of travel time observations recorded on several ocean bottom seismometers and gravity data collected during the TAICRUST experiment during 1995 (Wang *et al*, 2004). Figure 1 shows the experimental setup along with the locations of a NS trending seismic line 1 and EW trending seismic line-14 used in the present analysis. The crustal structure of Taiwan has been studied by several scientists (Mcintosh and Nakamura, 1998). With the goal of deriving crustal structure that is consistent with seismic and gravity observations, we employed our inversion algorithm to the data sets from Line 1 and Line 14.



Geology of the Area

The island of Taiwan is located along a segment of the convergent boundary between the Eurasian plate and the Philippine Sea Plate (PSP). East of the island, the Philippine Sea Plate has subducted northward beneath the Eurasian plate along the Ryukyu trench. South of the island, the Eurasian plate under-thrusts the Philippine Sea plate along the Manila trench. The understanding of the Taiwan Orogen and southern Ryukyu arc is still unclear due to the limited information about the geometry near the plate boundary.

Figure 1: Tectonic map and survey lines over Taiwan area

The velocity – density relation established by Godfrey *et al* (1997) is used for present scenario as it is suitable for the geological condition of our study area.

$$\rho(x,z) = a_1 + a_2 v(x,z) + a_3 v^2(x,z) + a_4 v^3(x,z) + a_5 v^4(x,z), \qquad (5)$$

Giving 80% and 20% weight to the seismic and gravity data set respectively, we performed the joint inversion of the travel time and gravity data. For Line-1, the velocity and density model of separate inversion along with the corresponding data match is displayed in Figure 2, whereas, figure 3 represents the same for joint inversion. It is observed that, though the quality of travel time fit of joint inversion is degraded (Figure 3b) compared to that from travel time inversion alone (Figure 2b), the agreement between the observed and computed gravity anomaly (Figure 3d) has improved to much more acceptable level.

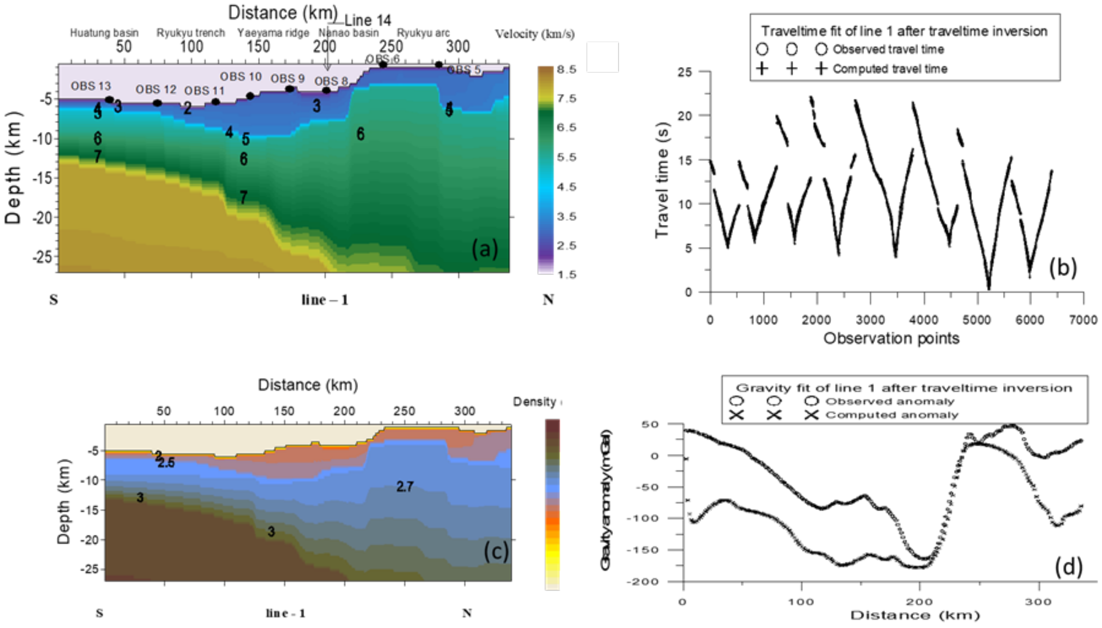


Figure 2: (a) velocity model from travel time inversion of line 1 and (b) the corresponding travel time data match. (c) density model obtained from velocity model and (d) the corresponding gravity data match (Roy et al., 2005)

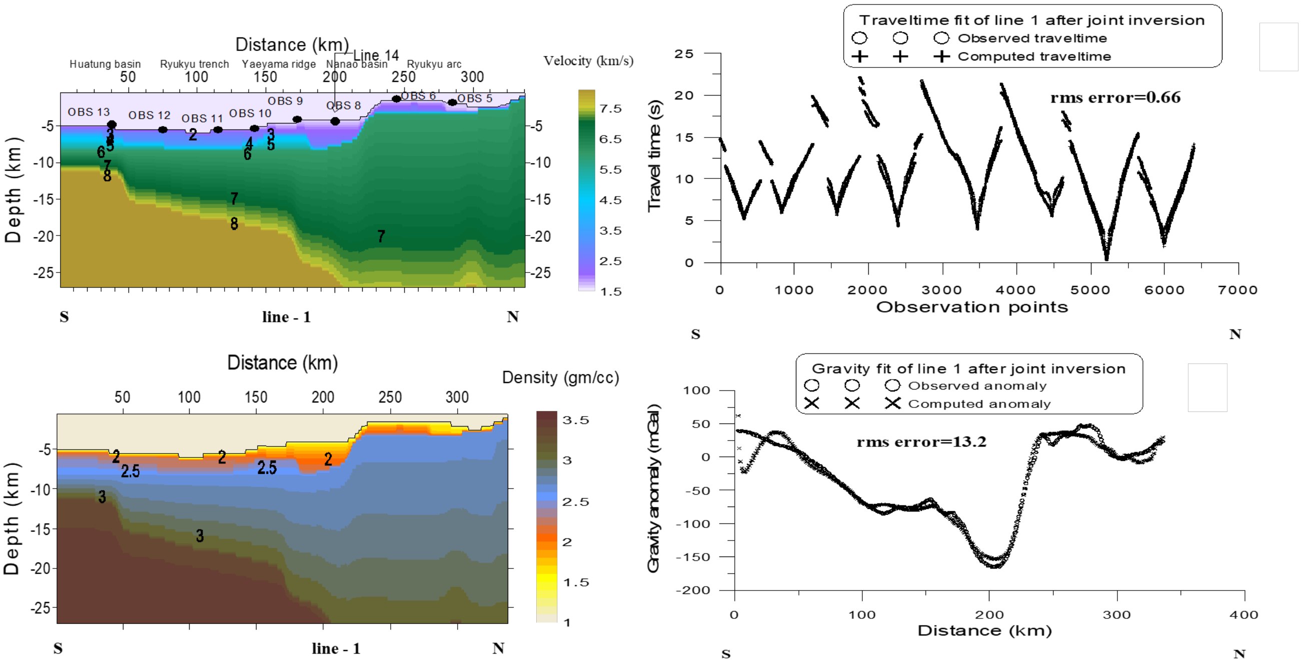


Figure (a) velocity model from joint inversion of line 1 and (b) the corresponding travel time data match. (c) density model obtained from velocity model and (d) the corresponding gravity data match (Roy et al., 2005)

Example 2. Constrained inversion of gravity and earthquake travel time data over Shillong Plateau: The northeastern part of Indian subcontinent constitutes one of the most active earth-quake regions of the world. One of the most important and geologically debatable geological feature of this area is Shillong Plateau. Shillong Plateau represents a horst and Rangpur Saddle constitute the corresponding graben as a result of multiple faults. The Bougour gravity anomaly map prepared by Mukhopadhaya (1974) and the high precision digital seismic network data recorded in the recent years by several institutes like National Geophysical Research Institute (NGRI), Manipur university, Gauhati university, Regional Research Laboratory-Jorhat (RRL-J), Tezpur university and Mizoram university are used for the study to delineate the complex structure of Shillong Plateau. Among hundreds of seismological stations, three stations, JPA, NGL and MND are found along the profile over which gravity inversion is carried out and so, the data of these stations are used for travel time inversion. Inversion of gravity data was performed first. The match between the observed and computed anomaly (Figure 4b) is found satisfactory. The inverted model is shown in Figure 4a.

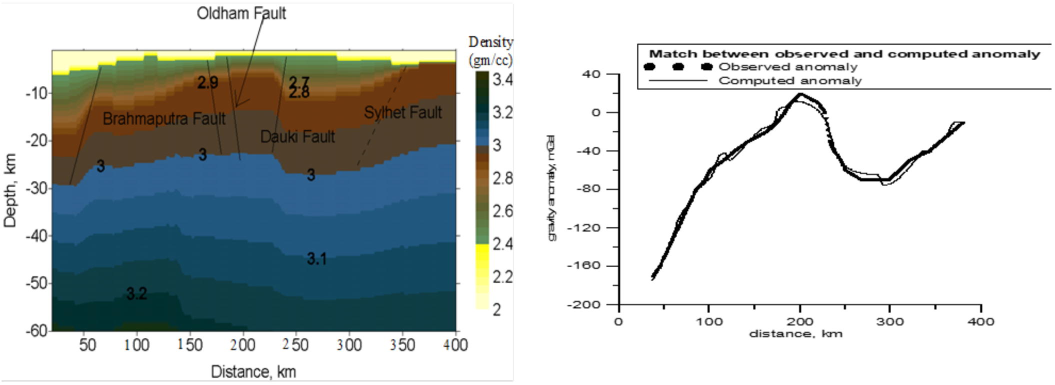


Figure 4(a) The density model and (b) data match from gravity inversion

The model shows 30-35 km thick crust with average density of 2.9gm/cc. The upper crust has the density varying from 2.7 – 2.8 gm/cc, whereas, the lower crust has density nearly 3 gm/cc. The crust is uplifted below the plateau. The Dauki fault is clearly delineated from the inverted model, whereas, the existence of the other fault in the northern side of the plateau (Oldham fault) is not very prominent. At the extreme south, there is another fault, which may be the Sylhet fault. The inverted model also indicates the presence of thick sediment in the northern part, i.e., in Brahmaputra Valley.

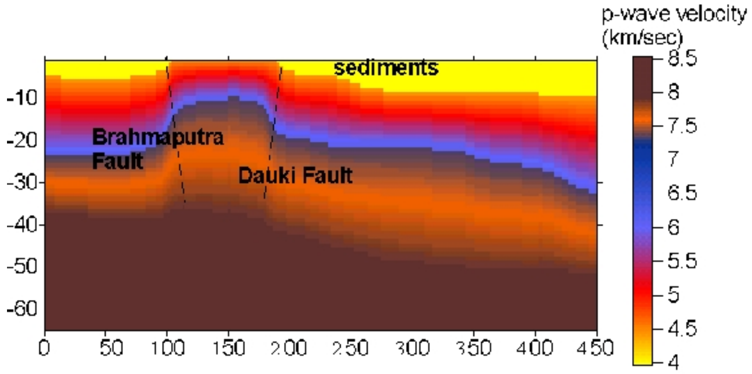


Figure 5. The velocity model obtained from constrained travel time inversion

The density values, obtained from gravity inversion, are considered to constrain the of p-velocity range. The inverted velocity model (Figure 5) shows a very clear pop-up structure below the Shillong plateau. The distance between two sharp edges is about 100 km. The distance between proposed Oldham fault and Dauki fault is about 70 to 80 km. This indicates that the northern fault, instead of Oldham fault, may coincide with Brahmaputra fault. Thick sediment is observed in both northern and southern side of the plateau. In northern part, it is due to the Brahmaputra valley and in the southern part it is due to Bengal basin. A 40-45 km thick crust is observed, which can be divided into upper and lower crust. The velocity of the crust varies from 5.5 to 7.5 km/sec. It is found that the density and velocity values are quite similar with the work by Nayak at el (2008).

Discussions and Conclusions

The crustal structure along and across the subduction zone of Taiwan is obtained from joint inversion of seismic travel time and gravity data. The use of arc tangent basis function decreases the number of model parameters without limiting the model flexibility, It has been observed that the convergence of VFSA is quite fast (400 to 600 iterations) for travel time inversion only, whereas, for joint inversion, it requires about 3000 to 4000 iterations to converge. Much care was taken to parameterize the model space and define the velocity density relationship so that geologically meaningful results could be derived from the data. Though, the travel time data match in joint inversion is compromised a little in comparison to that of travel time inversion, it is compensated with a much better match of gravity data and thus, satisfying both velocity and density model. Though the result over line -1 is only shown here, the results are similar for line-14 also. One important aspect of the inversion that has not been addressed here is that of uncertainty in the derived results, which is the area of future study.

The N-S profile across Shillong plateau is studied using gravity and seismic travel-time data. Here, the data quality is moderate and was suitable for joint inversion. So, both the data sets are inverted separately. The density structure obtained from gravity inversion is used to select the p-wave velocity range used for travel time inversion. The pop-up structure is not very clear in gravity inversion, but it is quite prominent in travel time inversion. The existence of sharp fault in both northern and southern side of the plateau is well delineated. The southern fault is clearly the Dauki fault, whereas, the northern fault may be the Bramhaputra fault. The distance between two edges is about 100 km. The distance between proposed Oldham fault and Dauki fault is about 80 km. So, the delineated fault is interpreted as the Bramhaputra fault.

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References

Godfrey N J, Beaudoin B C and Klemperer S L 1997 Ophiolitic basement to the Great Valley forearc basin, California, from seismic and gravity data: implications for crustal growth at the North American continental margin Geol. Soc. Am. Bull. 108, 1536–62

McIntosh, K. and Nakamura, Y. 1998. Crustal structure beneath the Nanaoo Forearc basin from TAICRUST MCS/OBS Line14. *Terr Atom Ocean Sc.,* 9, 345-362.

Mukhopadhyay, M., 1988, Gravity anomalies and deep structures of the Andaman arc, Marine Geophysical Researches, 9**,** 197-210.

Nayak, G. K., Rao, V. K., Rambabu, H. V. and Kayal, J. R., 2008, Pop-up tectonics of Shillong Plateau in the great 1897 earthquake (M 8.7); Insights from the gravity in conjunction with the recent seismological results.

Nielsen, L. and Jacobson, B. H. 2000. Integrated gravity and wide-angle seismic inversion for two-dimensional crustal modeling. Geophys J Int, 140, 222-232.

Rol, L., Sen, M. K., McIntosh, K., Stoffa, P. L., and Nakamura, Y., 2005, Joint inversion of first arrival seismic travel time and gravity data, J. Geophys. Eng, 2, 277-289.

Sen, M. K. and Stoffa, P. L. 1995. Global Optimization Methods in Geophysical Inversion. Elsevier Science Publishing Co

Strykowski, G. 1999. Some technical details concerning A new method of gravimetric-seismic inversion. Phys. Chem. Earth (A), 24, 207-214.

Wang, T. K., Lin, S. F., Liu, C. S., and Wang, C. S. 2004. Crustal structure of the southernmost Ryukyu subduction zone: OBS MCS and gravity modeling. *Geophys. J. Int.,* **157**. 147-163