Lowland Technology International 2015; 17 (3): 167-178
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

Using the memetic algorithm to determine the depths of sedimentary basins by 2-D gravity modeling

L.P. Toan [1] and D.V. Liet [2]

ARTICLE INFORMATION

Article history:

Received: 03 September, 2015
Received in revised form: 28 October, 2015
Accepted: 03 November, 2015
Published: December, 2015

Keywords:

Sedimentary basin
Parabolic density function
Memetic algorithm

ABSTRACT

In this article, the memetic algorithm using gravity data is applied to determine the thickness of a 2-D sedimentary basin whose density contrast varies with depth as a parabolic function. This memetic algorithm is a combination of the genetic algorithm and the Nelder-Mead Simplex local search to find optimal global solutions based on the minimum of the objective function, which is the total of data misfit ϕ_d and the 'norm' model ϕ_m and the second term is multiplied by the weight parameter namely a Tikhonov regularization. The program is written in Matlab. Firstly, it was tested on a synthetic model and the interpretable results are coincident with the model. Then, it was applied on An Giang and Dong Thap gravity anomalies in the Mekong Delta, Southwest of Vietnam, where the density contrast's function of sediment layers was found from the density contrasts of each layer of CL-1 well's stratigraphic column. The results showed that for both An Giang and Dong Thap anomalies, the observed and calculated gravity anomalies were fitted well, but the difference between the calculated depths using the memetic algorithm and the forward modeling method is slight because the approach to the solution of each method is different.

1. Introduction

In geophysics, the determination of sedimentary basin's thickness is a kind of gravity inverse problem. The most common method to solve this problem on computer is the forward modeling (FW) method which is performed by three steps: (1) to set up an initial model of a sedimentary basin based on geologic and geophysical knowledge; (2) the model's anomaly is calculated and compared with the observed anomaly based on the value of root mean square error; (3) and then, model's parameters are adjusted in order to improve the fit between the two above anomalies. This three-step process is repeated until these calculated and observed anomalies are sufficiently coincident (Blakely, 1995). The model of the sedimentary basin is often initialized as a polygon with M vertices or N vertical juxtaposed prisms and the solutions of the problem are the depths of vertices or the depths of the vertical prisms. Many authors have used this method and model as a set of vertical juxtaposed prisms with a constant density contrast (Bott, 1960) or density contrast varying with depth as a function of exponential (Cordell, 1973), parabola (Rao et al., 1993), and hyperbola (Rao et al., 1994).

In recent years, besides the rapid development of computer's technology, global optimization algorithms such as evolutionary and genetic algorithms have

[1] Corresponding author, PhD student, Mien Tay Construction University, Pho Co Dieu, 03, Vinh Long, VIETNAM, luongphuoctoan@gmail.com
[2] Associate Professor, University of science – HCM City, VIETNAM, dangvanliet@gmail.com
Note: Discussion on this paper is open until June 2016.

developed. These computational algorithms mimic the evolution of creatures in nature including initialization, selection, crossover, mutation, reproduction and replacement. These computational steps are similar to the three steps of the FW method as presented above. Therefore, many authors have used the genetic algorithm (GA) to solve the gravity inverse problem with the model as a polygon (Boschetti et al., 1997), (Liet, 2005), a set of vertical juxtaposed prisms (Toan et al., 2013, 2014), square plate (Krahenbuhl et al., 2006) or square prism (Montesinos et al., 2005, 2006). However, the GA often finds the approximation of global optimal solution because of confusion with the local optimum. Therefore, to well find the global optimal solution, in this paper, the memetic algorithm (MA), a hybrid genetic algorithm which is the combination of the genetic algorithm and local search method such as Nelder-Mead Simplex search (Nelder and Mead, 1965; Gao et al., 2010) is used (Moscato et al., 2003) and the model is a set of 2-D vertical juxtaposed prisms whose density is a parabolic function of depth (Rao et al., 1993). This method was tested on a synthetic model and then applied on An Giang and Dong Thap gravity anomaly profiles, in the Mekong Delta, Southwest of Vietnam.

2. Methodology

2.1 Modeling of a sedimentary basin and its gravity anomalies

Consider a 2-D model of sedimentary basin (infinite in y - direction) whose density is a parabolic function of depth that was composed by *N* vertical juxtaposed prisms. Their gravity anomalies are measured at the center of the prisms in the x-direction (Fig. 1a). Assuming that all the prisms have the same horizontal and their tops are at the ground surface (Fig. 1b).

In reality, the density of the sedimentary basin model increases with depth, so the density contrast between the sediments and basement will decrease with depth because the density of the basement is greater than the density of the sediments. Assuming that the density contrast varying with depth can be represented by a parabolic function as following (Rao et al., 1994):

$$\Delta\rho(z) = \frac{\Delta\rho_o^3}{(\alpha - \beta z)^2} \qquad [1]$$

where, $\Delta\rho(z)$ (g/cm^3) is the density contrast at the depth z (km), $\Delta\rho_0$ (g/cm^3) is the density contrast observed at the ground surface, α (g/cm^3) and β (g/(cm^{3}km)) are constants which can be obtained by fitting Eq. [1] from density contrast - depth data.

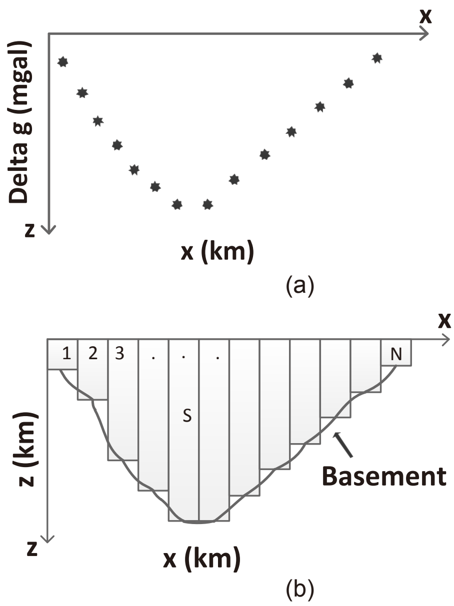

Fig. 1. Schematic illustration of a sedimentary basin. (a) The gravity anomaly produced by a sedimentary basin. (b) The model of sedimentary basin composed by N vertical juxtaposed prisms.

A gravity anomaly of the sedimentary basin's model at a certain point *i* comprises gravity anomalies of all the prisms:

$$g_i = \sum_{j=1}^{M} \Delta g_j(x_i),\ i = 1,2,\dots,N \qquad [2]$$

where, $\Delta g_j(x_i)$ is a gravity anomaly of the jth outcropping prism (z_1 = 0 and z_2 = z) at any point *i* and this anomaly is given by the following formula (Rao et al., 1994):

$$\begin{aligned}\Delta g(x_i) = 2G\Delta\rho_o^3[(T_1\theta_4 - T_2\theta_3) - (T_3\theta_1 - T_4\theta_2) \\ + \ln((\alpha - \beta z)/\alpha)(T_5 - T_6) - (T_5 \ln\frac{r_3}{r_2} - T_6 \ln\frac{r_4}{r_1})]\end{aligned} \qquad [3]$$

where, G is the gravitational constant and the other parameters are given as the following:

$$\begin{aligned}
T_1 &= \frac{\beta(x+w)^2 + \alpha z}{(\alpha - \beta z)(\alpha^2 + \beta^2(x+w)^2)} \\
T_2 &= \frac{\beta(x-w)^2 + \alpha z}{(\alpha - \beta z)(\alpha^2 + \beta^2(x-w)^2)} \\
T_3 &= \frac{\beta(x+w)^2}{\alpha(\alpha^2 + \beta^2(x+w)^2)} \\
T_4 &= \frac{\beta(x-w)^2}{\alpha(\alpha^2 + \beta^2(x-w)^2)} \\
T_5 &= \frac{(x-w)}{(\alpha^2 + \beta^2(x-w)^2)} \\
T_6 &= \frac{(x+w)}{(\alpha^2 + \beta^2(x+w)^2)}
\end{aligned} \qquad [3a]$$

$$r_1^2 = (x+w)^2, r_2^2 = (x-w)^2$$
$$r_3^2 = (x-w)^2 + z^2, r_4^2 = (x+w)^2 + z^2$$
$$\theta_1 = \begin{cases} \pi \ for\ x \geq 0 \\ 0 \ \ for\ x < 0 \end{cases}$$
$$\theta_2 = \begin{cases} \pi \ for\ x > 0 \\ 0 \ \ for\ x \leq 0 \end{cases} \quad [3b]$$
$$\theta_3 = \pi/2 + \tan^{-1}((x-w)/z)$$
$$\theta_4 = \pi/2 + \tan^{-1}((x+w)/z)$$

The details of the parameters are given in Fig. 2.

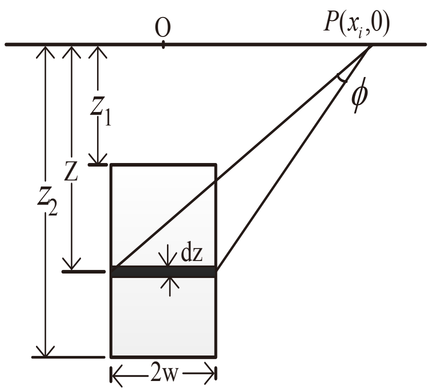

Fig. 2. The prismatic model.

2.2 Genetic algorithm (GA)

GA is a method for solving global optimization problems based on a natural selection process that mimics the biological evolution. The algorithm is started with a set of solutions (chromosomes or individuals), called population, which is randomly generated. Each individual of the population is evaluated by using the fitness function for searching an individual with the highest fitness through a series of three operators.

- Selection: Select a pair of individuals from the current population, with the probability of selection being an increasing fitness function, for crossover and mutation.

- Crossover: With probability p_c (the crossover probability), cross over a pair of parent chromosomes at a random chosen point to produce two offspring. For example, the strings 00010010 and **11110000** might be crossed over after the fourth position in each to produce 0001**0000** and **1111**0010 (two offspring).

- Mutation: With probability p_m (the mutation probability), a chosen random bit in an offspring is flipped to create a new individual. For example, the string 0**0**010010 might be mutated in its second position to produce 0**1**010010.

This process is repeated for the next generations until the best fitness individual is found or the number of generations is satisfied. The last best fitness individual is the best solution of the problem (Haupt et al., 2004).

2.3 Objective function

In order to evaluate individuals, the objective function (1/fitness function) is used and it consists of the weighted 'norm' model ϕ_m and data misfit ϕ_d as the following:

$$\phi = \phi_d + \beta_T \phi_m \quad [4]$$

where,

$\phi_d = \sum_{i=1}^{N} \frac{(g_{obs}^i - g_{cal}^i)^2}{N}$ is data misfit,

$\phi_m = \sum_{i=1}^{N} (z_{i-1} - z_i)^2$ is the model object function

and β_T is a Tikhonov regularization parameter to balance between ϕ_d and ϕ_m and ϕ stabilizes the solutions. There are several techniques which have been developed to estimate an appropriate regularization parameter β_T. Here, the L-curve is used to find a value of β_T (Krahenbuhl and Li., 2006).

Thus, the problem is to minimize the objective function (Eq. [4]).

2.4 Memetic algorithm (MA)

The limit of GA is just to find the approximate value of the optimal solution because of the influence of local optimum and slow convergence. To solve the bounds, the hybrid genetic algorithm, which is the combination of the genetic algorithm and local search method, is used and called the memetic algorithm (Krasnogor et al., 2005; García et al., 2008; Neri et al., 2012). There are two common traditional local search methods: quasi-Newton method and Nelder-Mead Simplex method. In this research, the Nelder-Mead Simplex method is used because this is a very classical and powerful local descent algorithm (Chelouah et al., 2003).

The Nelder-Mead algorithm was proposed to minimize a real function *f(x)* for $x \in R^n$. The method is started by an initial simplex with *n +1* vertices, each of which is a points in R^n and the simplex is transformed by using the iterative method through a sequence of four basic geometric transformations:

- Reflection (ρ): $x_r = (1+\rho)\bar{x} - \rho x_{n+1}$ [5]

where $\bar{x} = \sum_{i=1}^{n} x_i / n$

- Expansion (χ): $x_e = (1+\rho\chi)\bar{x} - \rho\chi x_{n+1}$ [6]

- Contraction (γ): $x_c = (1-\gamma)\bar{x} + \gamma x_{n+1}$ [7]

- Shrinkage (σ): $v_i = x_1 + \sigma(x_i - x_1)$ [8]

where *i = 2, . . . , n+1*.

After each appropriate transformation the current worst vertex is replaced by a better one. The iteration is continued to find the simplex satisfies: $f(x_1) \le f(x_2)) \le . . . \le f(x_{n+1})$ (Lagarias et al., 1998).

The local search can be incorporated at any stage such as initialization, selection, crossover and mutation (Kumar et al., 2013). Thus, in this paper, the local search acts on each individual pair after the selection stage to introduce new individuals to crossover and to accelerate the search towards global optimality.

The MA satisfies the 3 - step process of the FW. The calculated steps of the MA are also the same as the calculated steps of GA; however, MA includes the local search step and it is also used to solve the gravity inverse problem on computer. Thus, the MA is used to determine the depths of the sedimentary basin. The flowchart of the MA for the inverse gravity problem is given in Fig. 3.

The program is written in Matlab.

3. Testing program on a model

3.1 Model's details, density contrast function and gravity anomalies

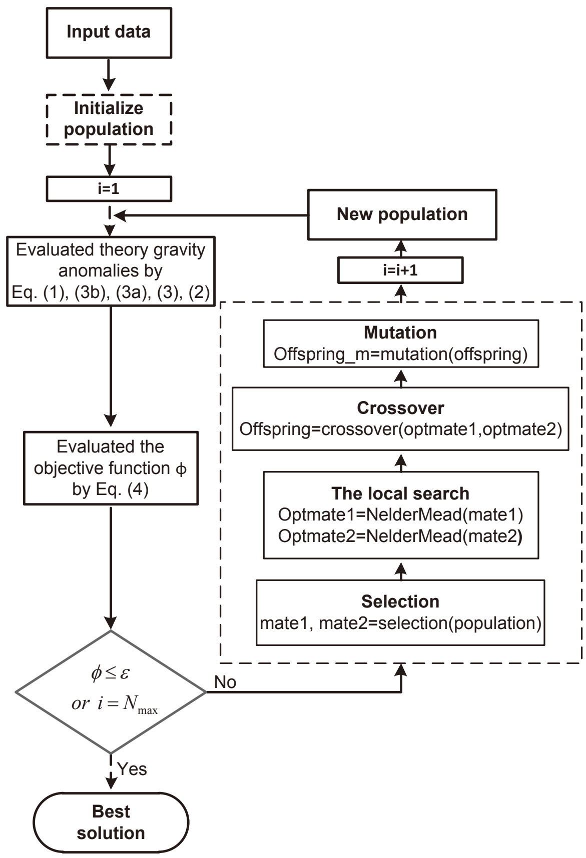

Fig. 3. Flowchart of the MA for the inverse gravity problem (Input data: Δg_{obs}: the observed gravity anomalies, $\Delta\rho_o$, β: density parameters, β_T: the Tikhonov regularization parameter, ε: the predetermined value (stopping criterion) and N_{max}: maximum loop (stopping criterion)).

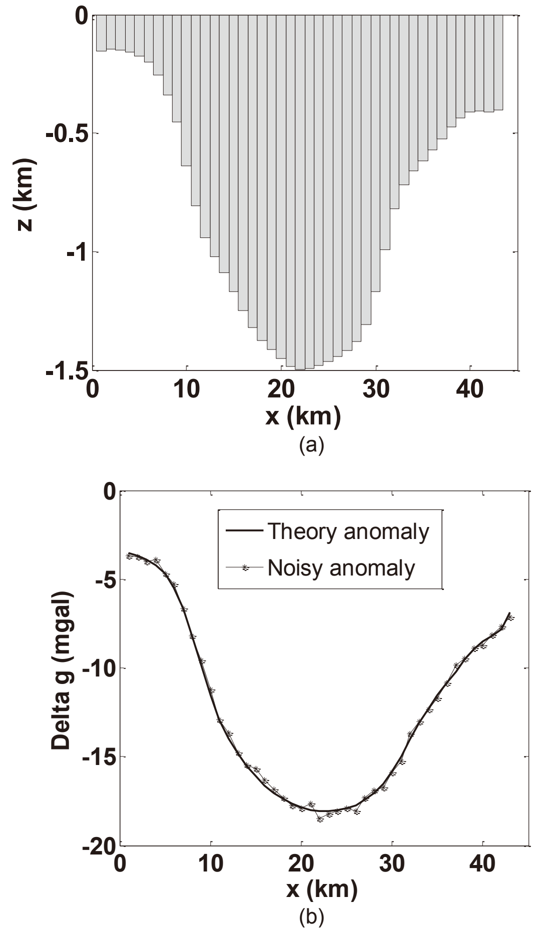

Fig. 4. (a) Vertical section of synthetic model. (b) Theory (line) and noisy (dots) anomalies.

The proposed model of a sedimentary basin consisting of 43 vertical juxtaposed prisms at an interval of 0.5 km along the x-axis and its density contrast is a parabolic function. The vertical section of this model is represented in Fig. 4a. The z_{max} = 1.498 km of the model is used to limit the depths of the computational model later. The function of density contrast could be referred Eq. [1] with the parameters: $\Delta\rho_o$ = - 0.55, α = - 0.55 and β = 0.2828.

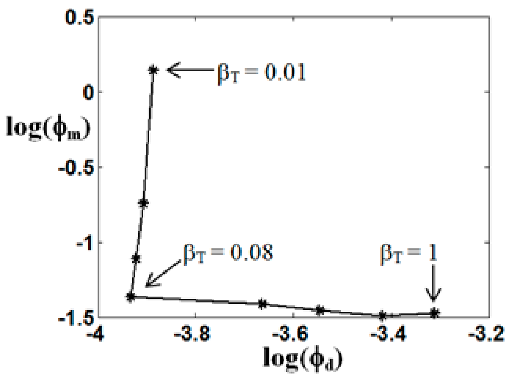

Fig. 5. The L curve to determine the Tikhonov regularization parameter.

Table 1. Model's gravity anomalies at some points.

Location of points	1	5	10	15	20	25	30	35	40
The theory gravity anomalies	-3.518	-4.721	-11.526	-16.124	-17.869	-17.915	-15.850	-11.538	-8.513
The noisy gravity anomalies	-3.707	-4.673	-11.233	-15.685	-17.892	-17.885	-15.902	-11.723	-8.753

Table 2. Values of β_T, ϕ_d and ϕ_m.

β_T	0.01	0.02	0.05	0.08	0.3	0.5	0.7	1
ϕ_d	0.0205	0.0201	0.0198	0.0196	0.0256	0.0288	0.0328	0.0365
ϕ_m	1.1490	0.4744	0.3299	0.2556	0.243	0.2331	0.2252	0.2295

Table 3. The objective function's values (ϕ) in 5 computation times of the model.

The objective function's values at the number of the loop of each computation							
No.	1	130	230	330	430	530	630
1	26.9401	0.1513	0.0456	0.0440	0.0436	0.0433	0.0430
2	35.4403	0.1568	0.0457	0.0441	0.0436	0.0434	0.0431
3	28.3054	0.0750	0.0451	0.0447	0.0439	0.0436	0.0432
4	23.7679	0.0657	0.0456	0.0445	0.0439	0.0434	0.0431
5	27.7960	0.1121	0.0471	0.0441	0.0435	0.0432	0.0429

Table 4. Some observed and calculated gravity anomalies of the model.

Location of points	1	5	10	15	22	25	30	35	40
The observed gravity anomalies	-3.707	-4.673	-11.233	-15.685	-18.485	-17.885	-15.902	-11.723	-8.753
The calculated gravity anomalies	-3.688	-4.646	-11.305	-15.884	-18.151	-18.015	-15.853	-11.632	-8.669

$$\phi_d = \sum_{i=1}^{N} \frac{(g_{obs}^i - g_{cal}^i)^2}{N} = 0.0196 \ (N = 43)$$

Table 5. Some real and calculated depths of the model.

Location of points	1	5	10	15	22	25	30	35	40
Depths of model	0.154	0.176	0.640	1.169	1.498	1.464	1.168	0.616	0.413
Calculated depths	0.168	0.177	0.617	1.096	1.519	1.519	1.171	0.667	0.451

$$\phi_m = \sum_{i=1}^{N} (z_{i-1} - z_i)^2 = 0.2913 \ (N = 43)$$

Replaced widths and depths of each prism of model and parameters of density contrast into Equations [3b], [3a], [3] and [2] to compute the theory gravity anomalies of the model at the center of each prism; after that, these values are corrupted by the addition of noise (plus 0.2 rand(size(g_{the})). The values of theory and noisy gravity anomalies of the model at some positions were extracted and given in Table 1. The theory (line) and noisy (dots) gravity anomalies of the model are represented in Fig. 4b.

3.2 Parameters of the memetic algorithm (MA)

The program is started by a random population. It is a set of individuals and each individual contains the solutions (unknowns) of the problem. According to Reeves, (1993) and Montesinos et al., (2005), a population size is chosen between 13 and 18 individuals for successful exploration of the solution space.

In this paper, a population containing 16 individuals is chosen; the crossover probability p_c = 0.5 and the mutation probability p_m = 0.1 (Haupt et al., 2004). The parameters of local Nelder-Mead Simplex search are chosen: ρ = 1 (reflection), χ = 2 (expansion), γ = 0.5 (contraction), and σ = 0.05 (shrinkage) (Lagarias et al., 1998).

3.3 Tikhonov regularization parameter

As presented in section 2.3, there was the Tikhonov regularization parameter β_T in the objective function (Eq. [4]). To determine this parameter, the memetic algorithm is used with 8 different Tikhonov regulation parameters to compute the thickness of the above model from noisy gravity anomaly. With each Tikhonov parameter, the inverse problem is computed in 630 generations (630 loops) to find ϕ_m and ϕ_d. The results are given in Table 2.

To estimate the best regularization parameters β_T, the L-curve method is used by plotting log(ϕ_d) versus log(ϕ_m), and the logarithmic graph is showed in Fig. 5. The value β_T at the 'elbow' of this curve is the best Tikhonov regulation parameter (Krahenbuhl and Li, 2006). This parameter plays a role to balance between two errors ϕ_m and ϕ_d in the objective function; hence, solutions of the problem are not dispersive but they converge rapidly.

The results show that the best parameter is β_T = 0.08; the objective function is:

$$\phi = \phi_d + 0.08\phi_m \quad [9]$$

Eq. [9] is used to find the solution of the sedimentary basin for synthetic model and real data.

3.4 Determining the thickness of the model's sedimentary basin

The noisy gravity anomaly (dots) in Fig. 4b is used as the observed data to determine the depths of model's sedimentary basin because the real data always contain noises. The model comprises 43 prisms, therefore the solution of the problem also comprises 43 unknowns that are the depths z_i of each prism. Thus, each individual (chromosome), a set of unknowns, must contain 43 genes (43 unknowns). They are initialized randomly between z_{max} ± 100 % (0 km ≤ z_i ≤ 2.997 km). The number of individuals of the population and other parameters of MA were presented in section 3.2. The stopping criteria of computation are either the objective function's value of the best individual ϕ ≤ 0.001 (ε = 0.001) or the number of generations evolution equal to N_{max} = 630.

The inverse problem is solved 5 times. In each computation, the best solution was found after 630 generations (the 2nd stopping criterion). Table 3 shows the values of objective function according to the number of generation of each computation time, and Fig. 6 represents these values in term of semilogarithmic graph. They also show that the problem is almost convergent after 230 generations. Therefore, it is necessary to present the results of the 5th computation time with ϕ = 0.0429 at the 600th generation.

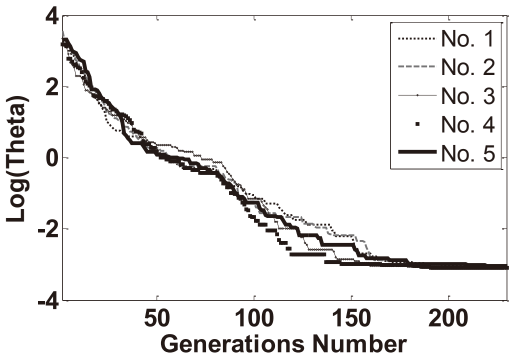

Fig. 6. The objective function's values in 5 times of computation.

. Some extraction results of the observed and calculated gravity anomalies are given in Table 4. The observed (dots) and the calculated (line) gravity anomalies are represented in Fig. 7; they show that the closeness of fit between the two anomalies with the data misfit ϕ_d = 0.0196.

Table 5 represents some depth values that were extracted from the real and calculated depths of the model. The geometry of the model (dots) and the calculated depths (line) are represented in Fig. 8. They show that both real depths (maximum depth is 1.498 km) and calculated (maximum depth is 1.519 km at the 22th prism) are almost approximate.

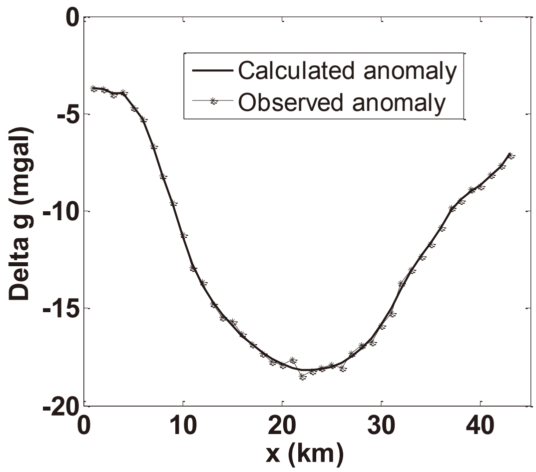

Fig. 7. Observed (dots) and calculated (line) gravity anomalies.

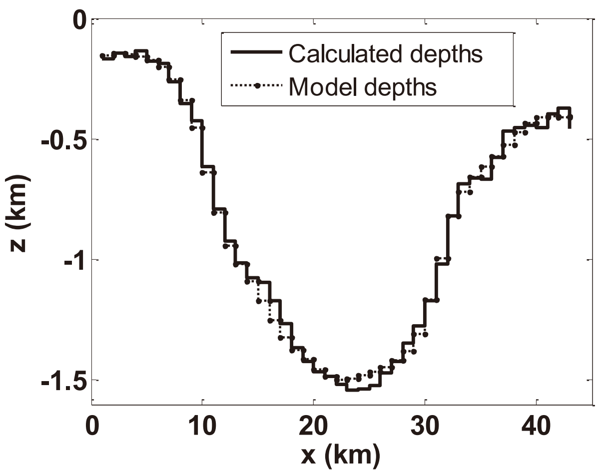

Fig. 8. Depths of model: real depths (dots), calculated depths (line).

The testing program on the model successfully obtained, therefore this method is applied in order to solve the following real problems.

4. Application on gravity data in the Mekong Delta–Southwest of Vietnam and discussions

The Mekong Delta (Fig. 9) is a region in the Southwest of Vietnam where the Mekong River approaches and empties into the sea via a network of distributaries. The Mekong Delta region encompasses a large portion of Southwestern Vietnam of 39,000 square kilometers, and almost all the area is covered with water, according to the season. The geological structure of the Mekong Delta could be divided into three zones and a bead: they are Bien Hoa swell, Can Tho basin, Ha Tien swell and Soc Trang swell bead.

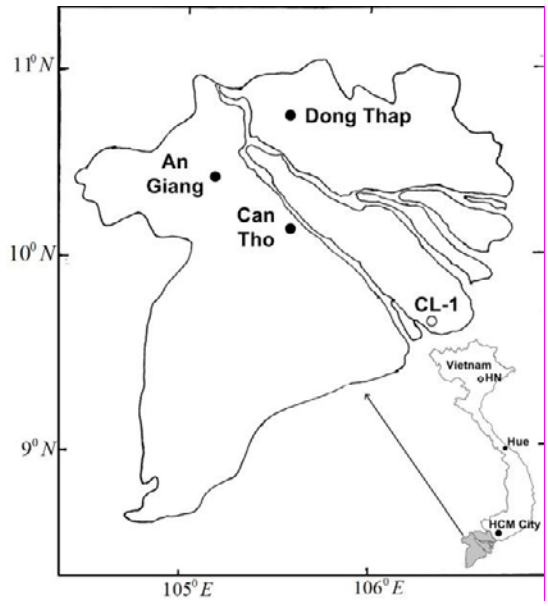

Fig. 9. The Mekong Delta - Southwest of Vietnam.

Bouguer gravity anomalies of the Mekong Delta were measured by Cuu-Long Petroleum Agency from 1971 to 1981 (Quyet, P. D., 1985). In this paper, two profiles of An Giang and Dong Thap gravity anomalies in Cantho basin are interpreted.

4.1 The function of density contrast

In the Mekong delta, there are two deep wells: Phung-Hiep well (800 m) and CL-1 well (2100 m). The density contrasts of each layer of the stratigraphic column of CL-1 well (Liet, D. V., 1995) are used as the input data to determine the parameters of the density contrast of depth which is the parabolic function (Eq. [1]) using the least square nonlinear regression method. The results show as the following:

$$\Delta\rho(z) = \frac{-0.55^3}{(-0.55 - 0.2828z)^2} \quad [10]$$

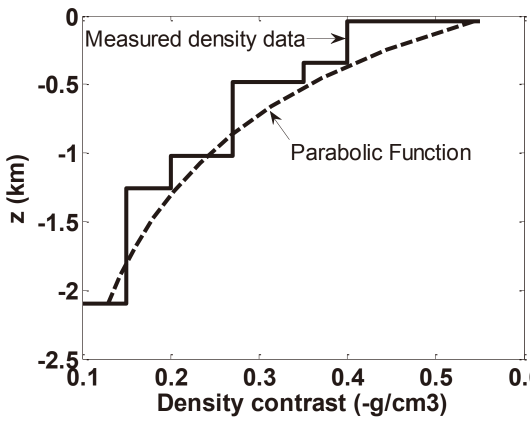

Fig. 10. Approximation of real density contrast - depth data by parabolic function.

The graph of measured density contrasts of the stratigraphic column of CL-1 and the graph of the parabolic function are represented in Fig.10. The values of parameters in Eq. [10] are $\Delta\rho_0$ = - 0.55, α = - 0.55, β = 0.2828 which are used to compute the thickness of the sedimentary basin in the Mekong Delta.

4.2 Data

The observed gravity anomalies are Bouguer anomalies that are the sum of regional anomalies and residual (local) anomalies. In the interpretation of the thickness of the sedimentary basin, the residual anomalies are used. The residual anomalies are equal to Bouguer anomalies minus to regional anomalies. In this paper, the regional anomalies are computed by the least square method using a second polynomial in two variables of latitude and longitude of measured positions.

4.3 Interpretation of An Giang gravity anomaly

The profile of residual gravity anomalies of An Giang is in the direction of the Northwest (10°22' N, 105°12' E) – Southeast (10°12' N, 105°21' E). There are 49 measured points with equal interval 0.5 km and minimum value Δg_{min} = - 21.9 mgal, thus, the approximate maximum depth of its source is z_{a_max} = 1.858 km (the thickness of an infinite slab based on the minimum value of gravity anomaly). This value is used to limit the depths of the computational model later. Fig. 12 represented the observed negative gravity anomalies (dots) of this profile whose graph appears as a parabolic shape with its vertex at the bottom. This negative gravity anomaly style showed that its source is a sedimentary basin. Therefore, the memetic algorithm can be used to determine the thickness of its source.

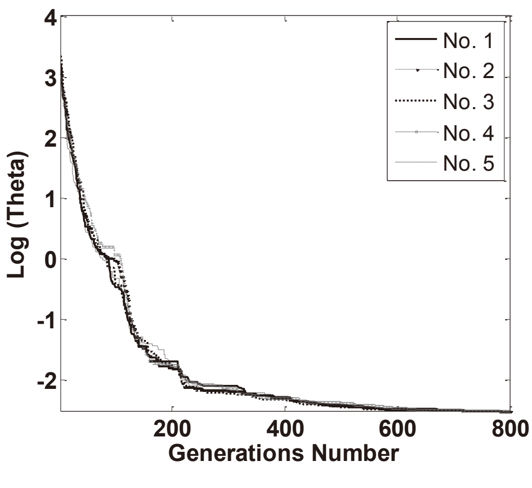

Fig. 11. The objective function's values of An Giang anomaly in 5 times of computation.

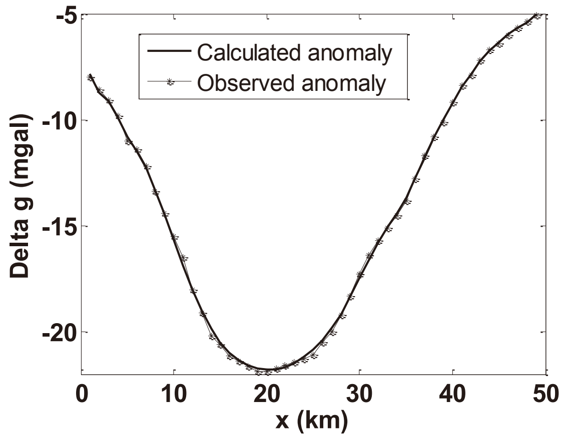

Fig. 12. Observed (dots) and calculated (line) An Giang gravity anomalies.

The model of the inverse problem is the sedimentary basin which comprises 49 vertical juxtaposed prisms at an interval of 0.5 km along the x- axis, and its density contrast varies with depth as a parabolic function (Eq. [10]), and the measured points at the center of each prism. With this model, the solution of the problem comprises 49 unknowns, consequently, each individual contains 49 genes. They are initialized randomly between $z_{a\_max} \pm 100$ % (0 km $\le z_i \le$ 3.715 km). The number of individuals of the population and other parameters of MA are presented in section 3.2, and the stopping criteria are either the objective function's value of the best individual $\phi \le$ 0.001 (ε = 0.001) or the number of generations evolution equal to N_{max} = 1000.

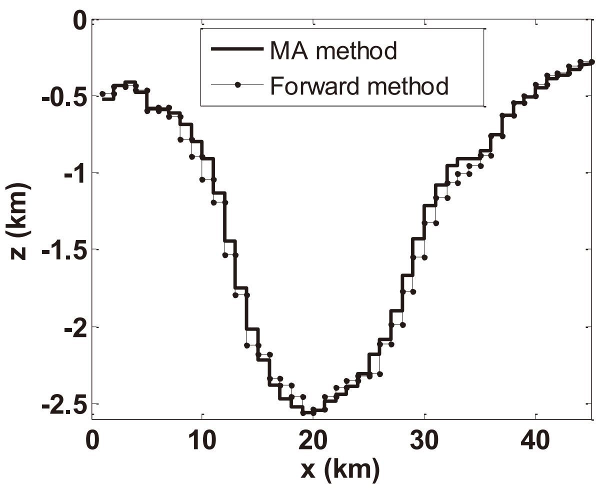

Fig. 13. Geometry of sedimentary basin of An Giang: MA method (line), FW method (dots).

The inverse problem is also computed 5 times. In each computation, the best solution is found after 1000 generations (the 2nd stopping criterion). Table 6 shows the values of objective function according to the number of generation of each computation time. Fig. 11

Table 6. The objective function's values (ϕ) in the 5 computation times of An Giang.

The objective function's values at the number of loop of each computation							
No.	1	100	200	400	600	800	1000
1	24.5425	0.6261	0.1861	0.0997	0.0827	0.0791	0.0778
2	20.9287	0.9651	0.1658	0.1040	0.0857	0.0816	0.0788
3	28.6116	0.6659	0.1652	0.0986	0.0830	0.0797	0.0784
4	20.3527	1.0720	0.1737	0.1005	0.0854	0.0810	0.0783
5	23.5532	0.7295	0.1684	0.1029	0.0852	0.0791	0.0779

Table 7. Some observed and calculated gravity anomalies of An Giang.

Location of points	5	10	15	20	25	30	35	40	45
The observed gravity anomalies	-11	-15.5	-20.6	-21.9	-21.1	-17.3	-13.8	-9.2	-6.4
The calculated gravity anomalies	-10.78	-15.63	-20.47	-21.78	-20.85	-17.49	-13.67	-9.22	-6.38

$$\phi_d = \sum_{i=1}^{N} \frac{(g_{obs}^{i} - g_{cal}^{i})^2}{N} = 0.0169 \ (N = 49)$$

Table 8. Some depths of An Giang anomaly calculated by MA's algorithm and FW method.

Location of points	5	10	15	20	25	30	35	40	45
Calculated depths by MA	0.583	0.909	2.214	2.545	2.182	1.216	0.860	0.447	0.293
Calculated depths by FW	0.599	1.046	2.184	2.539	2.307	1.326	0.886	0.428	0.278

represents these values in form of semilogarithmic graph. This shows that the problem is almost convergent after the 600th generation.

The first computation time with its minimum value of objective function ϕ = 0.0778 is chosen to present the results. Some observed (g_{obs}) and calculated (g_{cal}) anomalies are showed in the Table 7. The observed (dots) and the calculated (line) gravity anomalies are represented in Fig. 12 with the data misfit ϕ_d = 0.0169.

Because there is not any well near An Giang anomaly, it is difficult to verify the depth results of MA method. To overcome this problem, the FW method is applied to estimate the depths of this anomaly and to compare all depth results. Some calculated thickness of An Giang sedimentary basin using MA's algorithm (data misfit is 0.0169) and FW method (data misfit is 0.1211) are given in Table 8. The calculated thickness using MA's algorithm (line) and FW method (dots) for An Giang profile are represented in Fig. 13 with the maximum depth 2.558 km and 2.557 km, respectively. Although the maximum calculated depths of the two methods are coincident but two graphs in Fig. 13 shows that there are some different that will be discussed in section 4.5.

4.4 Interpretation of Dong Thap gravity anomaly

The profile of residual gravity anomalies of Dong Thap is in direction Southeast (10^{o}21' N, 105^{o}33' E) – Northwest (10^{o}17' N, 105^{o}43' E). There are 35 measured points at equal interval 0.5 km and minimum anomaly value Δg_{min} = -13.2002 mgal; therefore, the approximate maximum depth of its source is z_{b_max} = 0.8117 km. The computation of the thickness of sedimentary basin performed in Dong Thap is similar to the An Giang anomaly but the difference is the number of observed points (35 points) so the model of sedimentary basin of Dong Thap only comprises 35 vertical juxtaposed prisms.

Fig. 14 represents the objective function's values in the form of semilogarithmic in accordance with the generations in 5 times of computation. They also show that the problem is almost convergent after the 600th generation.

As presented above, the computed results with its value of objective function minimum ϕ = 0.0102 are chosen to present the results. The graph of the observed (dots) and calculated (line) gravity anomalies is represented in Fig. 15. They show that two anomalies significantly agree with data misfit ϕ_d = 0.0006.

Fig. 16 represents the computed thickness of Dong Thap sedimentary basin using MA's algorithm (line) with the maximum depth of 0.925 km and the other one using FW method (dots) with the maximum depth of 0.873 km. The data misfit of FW method (0.0423) is larger than the data misfit of MA (0.0006).

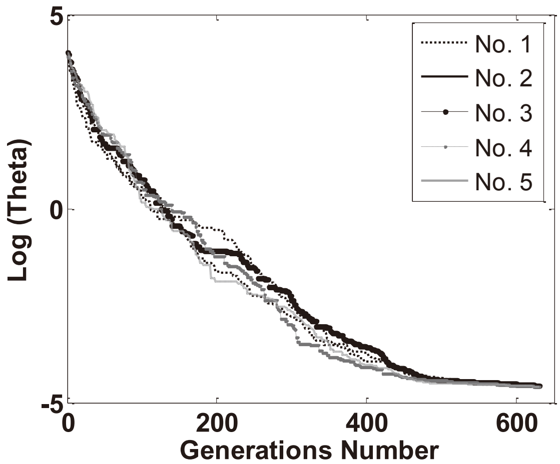

Fig. 14. The objective function's values of Dong Thap anomaly in 5 times of computation.

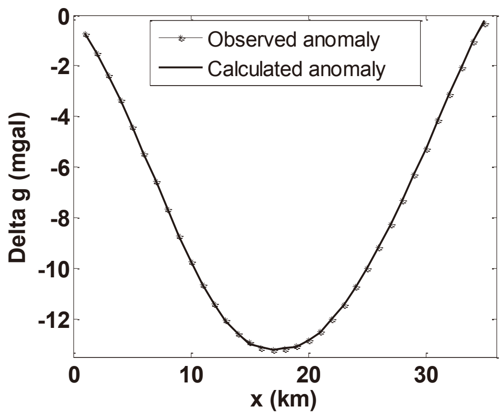

Fig. 15. Observed (dots) and calculated (line) Dong Thap gravity anomalies.

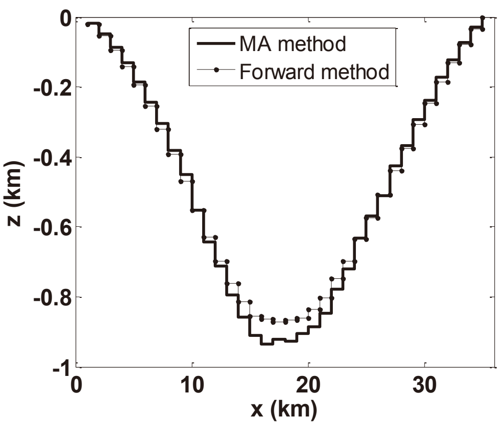

Fig. 16. Geometry of sedimentary basin of Dong Thap: MA method (line), FW method (dots).

4.5 Discussions

The results in 4.3 and 4.4 sections show that the accuracy of the observed and calculated anomalies for both An Giang and Dong Thap profiles is significantly compatible with data misfits of 0.0169 and 0.0006, respectively. But the calculated depths using the MA and the FW methods for both An Giang and Dong Thap anomalies are slightly different because the approach to the solution of each method is different. Indeed, the FW method used the formula of an infinite slab to initialize one model, and then the depths of this model were adjusted based on the differences between the observed and calculated anomalies by one formula. Thus, the solution is poor (only one model) and subjective (one formula). Meanwhile, the MA's algorithm is started with many models which are randomly initialized. These models are adjusted by genetic operators and the calculations based on random numbers. By the end of the computation, the best model among many other models is selected. This solution is rich (selecting one model from many models) and objective (using genetic operators and random numbers). So it could deduce that the calculated depths using the MA's algorithm are reasonable.

5. Conclusions

The memetic algorithm, which is the combination of the genetic algorithm and the Nelder-Mead Simplex local search, has been developed in order to determine the thickness of the sedimentary basin with the parabolic density contrast. This program was tested on the synthetic model and then was applied on the two measured gravity profiles in the Mekong Delta – Southwest of Vietnam. The interpretation of the model showed that there are the coincidence between the initial model and the calculated model, and the theory and calculated gravity anomaly's model are well suitable.

In the real cases, the memetic algorithm was used to interpret An Giang and Dong Thap gravity profiles. Since there aren't deep wells near the two gravity profiles, practically, it is difficult to verify the calculated geometry of sources. To solve this problem, the calculated geometry of sources using the MA's algorithm and FW method for both profiles are compared and the results showed that there are no significant differences. In addition, the results also showed that the observed and calculated gravity anomalies are fit together for both An Giang and Dong Thap profiles. These results are an important premise to solve a 3-D inverse gravity problem by using the MA, as suggested for further research.

Acknowledgements

The authors thank University of Science – HCM City where enabled us using tools and documents to finish this paper.

References

Blakely, R.J., 1995. Potential Theory in Gravity and Magnetic Applications. Cambridge University Press, New-York.

Boschetti, F. and Dentith, M., 1997. Inversion of potential field data by Genetic algorithms. Geophysical Prospecting, **45**: 461-478.

Bott, M. H. P., 1960. The use of rapid digital computing methods for direct gravity interpretation of sedimentary basins. Geophysical J. the Royal Astronomical Society, **3**: 63-7.

Chelouah, R. and Siarry, P., 2003. Genetic and Nelder–Mead algorithms hybridized for a more accurate global optimization of continuous multiminima functions, European J. Operational Research, **148**: 335-348.

Cordell, L., 1973. Gravity analysis using an exponential density-depth function-San Jacinto Graben, California. Geophys, **38**: 684 690.

Gao, F. and Han, L., 2010. Implementing the Nelder-Mead simplex algorithm with adaptive parameters. Springer, Published online, Comput Optim Appl DOI 10.1007/s10589-010-9329-3.

García, S., Cano, J. R. and Herrera, F., 2008. A memetic algorithm for evolutionary prototype selection: A scaling up approach, Pattern Recognition, **41**: 2693-2709.

Haupt, R.L. and Haupt, S.E., 2004. Practical Genetic Algorithms. John Wiley & Sons, Inc., New Jersey.

Lagarias, J. C., Reeds, J. A., Wright, M. H. and Wright, P. E., 1998. Convergence properties of the Nelder-Mead Simplex method in low dimensions. Society for Industrial and Applied Mathematics, **9**(1): 112-147.

Krahenbuhl, R. A. and Li, Y., 2006. Inversion of gravity data using a binary formulation. Geophys. J. International, **167**: 543–556.

Krasnogor, N. and Smith, J., 2005. A Tutorial for Competent Memetic Algorithms: Model, Taxonomy, and Design Issues. IEEE Transactions on Evolutionary computation, **9**(5): 474-488.

Kumar, R., Tyagi, S. and Sharma, M., 2013. Memetic Algorithm: Hybridization of Hill Climbing with Selection Operator. International J. Soft Computing and Engineering (IJSCE) ISSN: 2231-2307, (**3**): 2.

Liet, D.V., 2005. Determination of the crystal – basement from gravity data using genetic algorithms, J. Science and Technology Development, **8** (12): 90-96 (Vietnamese).

Liet, D.V., 1995. Analysis of combined gravity and magnetic data in the South of Vietnam, Ph.D. thesis, University of Ho Chi Minh City (Vietnamese).

Montesinos, F. G., Arnoso, J. and Vieira, R., 2005. Using a genetic algorithm for 3-D inversion of gravity data in Fuerteventura (Canary Islands). International J. Earth Sci. (Geol Rundsch) **94**: 301-316.

Montesinos, F. G., Arnoso, J., Benavent , M. and Vieira, R., 2006. The crustal structure of El Hierro (Canary Islands) from 3-D gravity inversion. J. Volcanology and Geothermal Research, **150**: 283- 299.

Moscato, P. and Cotta, C., 2003. A gentle introduction to memetic algorithms. In: (**315**): 105-144.

Nelder, J. A., and Mead, R., 1965. A Simplex Method for Function Minimization. The Computer J., **7** (4): 308-313.

Neri, F. and Cotta, C., 2012. Memetic algorithms and memetic computing optimization: A literature review, Swarm and Evolutionary Computation, **2**: 1–14.

Quyet, P. D., 1985. Using gravimetric method to study geological structure in Mekong Delta. The doctoral thesis, Hanoi University of Mining and Geology (Vietnamese).

Rao, C. V., Chakravarthi, V. and Raju, M. L., 1993. Parabolic density function in sedimentary basin modelling. Pageoph, **140** (3): 493-501.

Rao, C. V., Chakravarthi, V. and Raju, M. L., 1994. Forward modeling: gravity anomalies of two-dimensional bodies of arbitrary shape with hyperbolic and parabolic density functions. Computers & Geosciences, **20 (**5): 873-880.

Reeves, C. R., 1993. Using genetic algorithms with small populations. Proc. 5th International Conf. Genetic Algorithms, University of Illinois at Urbana-Champaign, Morgan Kaufmann Publishers: 92-99.

Toan, L. P., Hao, N. A., Nhanh, B. T. and Liet, D. V., 2013. Inversion of gravity data using genetic algorithms. J. Marine Science and Technology, **13**(3A): 24-33 (Vietnamese).

Toan, L. P. and Trinh, D. D., 2014. Determination of the crystal basement of some gravity anomalies in Mekong Delta using binary genetic algorithm. J. Science Can Tho University, **32A**: 1-9. (Vietnamese).

Symbols and abbreviations

$\Delta\rho$	Density contrast at the depth
$\Delta\rho_0$	Density contrast at the ground surface
α, β	Constants of the function density
G	Gravitational constant
p_m	Mutation probability
p_c	Crossover probability
ϕ_d	Data misfit
ϕ_m	Model object function
ϕ	Objective function
β_T	Tikhonov regularization parameter
ρ	Transformation of reflection
χ	Transformation of expansion
γ	Transformation of contraction
σ	Transformation of shrinkage
ε, N_{max}	stopping criteria
FW	Forward modeling
GA	Genetic algorithm
MA	Memetic algorithm