CHAPTER 4

Result and Discussion

The objective of this thesis is to modify and develop MATLAB code for Full Waveform Inversion (FWI). The developed FWI code was applied to a complex model to evaluate its usefulness for velocity updating. The specific model tested, the Mamousi model shown in Figure 4.1. This is a complex structure model with large normal fault, steep dip reflector, and strong velocity variation.

In this study, 19 shot gathers were generated along the surface with 160 m shot spacing, 200 active receivers for each shot and 10 m receiver spacing. Ormsby wavelet described on Figure 3.2 was used as source wavelet. The record length 1.5 seconds and 4ms sampling interval are sufficient for this test model.

4.1 Application of Full Waveform Inversion

The following section will show the capabilities of the full waveform inversion algorithm uses to recover the velocity model. The algorithm is applied to the smoothed version of the Marmousi model, which is used as an initial model and tried to estimate the true velocity model.

4.1.1 True and initial velocity model

To reduce a computational time, part of Marmousi model was selected, and used as a test model. The selected model is 3.2 km long by 1.0 km depth with 10m by 10m cell size cover the complex fault zone as shown on Figure 4.1. A smoothed version of the original Marmousi model was used as initial model for evaluate the full waveform inversion algorithm. A 2D mean filter with filter window 200m by 200m was applied to obtain a smoothed version of velocity model, as shown on Figure 4.2 and Figure 4.3. The initial velocity model is used for the FWI algorithm must contain a low frequency component of the true model to avoid a local minimise problem. Then, FWI will use to recovery the high frequency component of the velocity model.

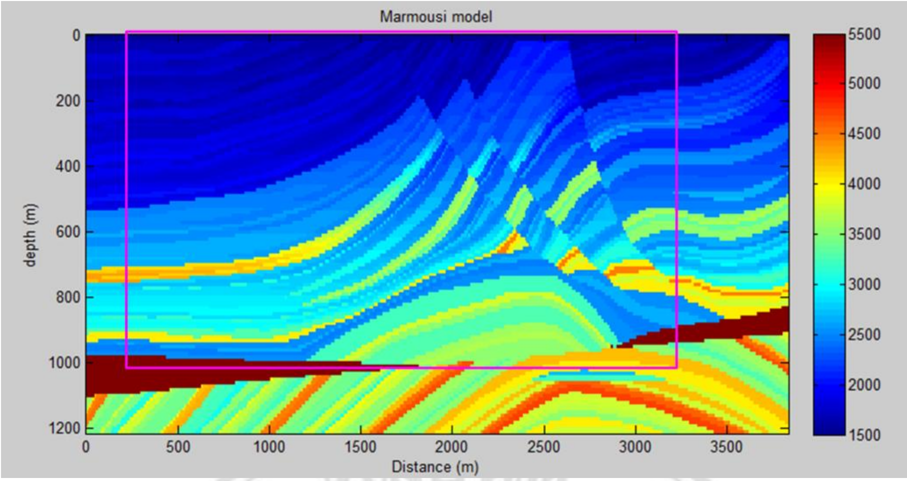

Figure 4.1 Original Marmousi model with selected area, 3.2 km long by 1.0 km depth with 10m by 10m cell size for test model.

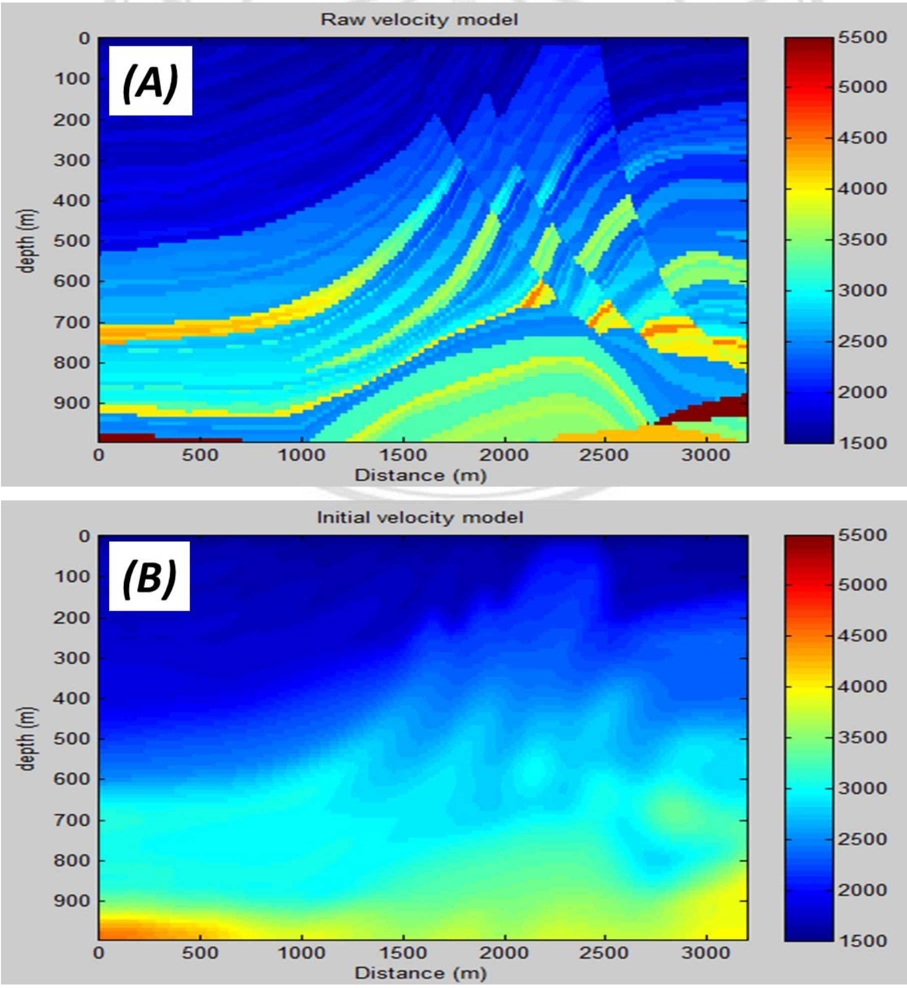

Figure 4.2 (A) true velocity model and (B) smoothed version of Marmousi model used as initial velocity model.

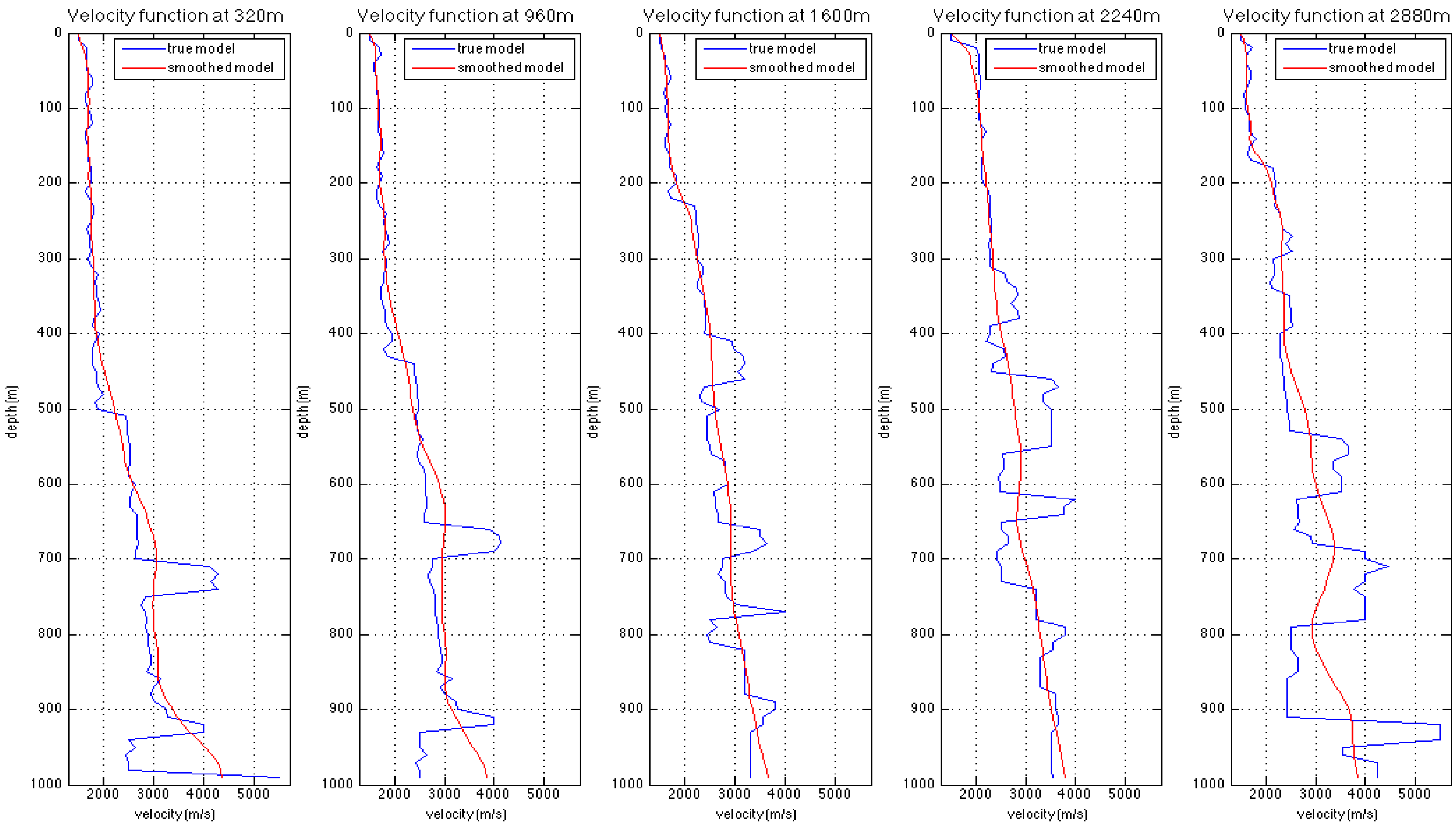

Figure 4.3 the velocity function at 320m, 960m, 1600m, 2240m and 2880m offset, comparing between true velocity function and initial velocity function on Figure 4.2

4.1.2 Gradient of misfit function

To update the initial velocity model with FWI, the gradient of misfit function needed to be calculated to estimate the perturbation of model. The results of the gradient of misfit function, Figure 4.4 and 4.5 show a good resemblance to the true velocity model, especially on the complex structure zone, the steep dipping layers and large normal faults. On the shallow part of the model, small details of the velocity variation are well defined with relatively small amplitude of the gradient of misfit function. The high velocity layers also well recovered and represent as a strong magnitude in the section.

Figure 4.4, depicts stronger amplitudes on the shallow part of the gradient of misfit function from iteration01. This is related to high contrast of the velocity that is observed from the velocity function at distance 2240 m shown in figure 4.3. When comparing the overall amplitude of the gradient of misfit function in Figure 4.4 and 4.5, the amplitude decreased respectively with an increasing number of iteration.

4.1.3 Model perturbation and updating

As mentioned in the previous section, the gradient of misfit function is used to highlight missing information of the initial velocity model. This amplitude information is then transformed into the perturbation model by applying a constant scale.

The scaling was estimated based on the value that minimise the misfit function. Figure 4.6 shows an example of the scale search which is calculated from 9 sampling shot gathers. The scaling resulted in a minimum misfit function value of 35 that was then used to calculate the perturbation model. The scale estimation has to be calculated individually for each of iterative inversion. The function of scale estimation is to determine how far the model can be updated with this gradient of misfit function. Figure 4.7 illustrates that the different scaling was selected for calculated model perturbation on different iteration.

Figure 4.8 and 4.9 are examples of the model recovery after several inversions. The overall result of the final velocity model shows a good resemblance to the true velocity model, including features like fault plane and high velocity layer. On the shallow part of the model, the small variations in the velocities are updated to the new model, which then fit quite well to true model. On the deeper part, high velocity layers are well defined, as well as fault location and the contrast of the velocity on both side of normal fault. Below 700m, the folding or antiform structure are overall well recovered after update, but the detail of the high velocity layer inside was not clearly define. Figure 4.10, shows the comparison of the velocity profiles between the true velocity model, the initial velocity model and the updated velocity model after 20 iterations at different location, 960m 1600m and 2240m. This assumes that the velocity information is available from well log at that location to control the result. The results show a good improvement after several inversions and the overall shape of the velocity profile is roughly the same with the true model, especially on the shallow part which matches with the true model quite well. For the deeper part, the high velocity layers that do not exist on the initial model are well defined and updated to the model. Even though, an overall good result has been shown, the final velocities are slightly lower (10%) than the true model, which therefore requires more iteration to refining the final model

4.1.4 Monitoring with misfit function

The updated model's misfit function was calculated to be compared and is shown in Figure 4.11. The values are rapidly decreasing at the beginning, especially on the first 6 iteration but the misfit function show a slightly decreasing or constant value after 15th iterations. It indicates that the inversion is not effective update of the model.

4.1.5 Monitoring with synthetic data and data residual

Other than the misfit function, the synthetic data and the data residual could also be used to monitor the result of inversion. Synthetic gather generated from the velocity with more iteration of inversion, should be more close to the raw gathers than the gathers generated from initial model. On the other hand, the amplitude of the data residual should be reduced with more iteration. Figure 4.12 and 4.13, comparing the raw shot gather with the synthetic shot generated from updated models. The results show that the restoration of the reflection wave respective to the number of the iterations. Figure 4.15 and 4.16 present the data residual calculated from different iterations of velocity model. The result shows that high amplitudes are found on the beginning of the iteration, however with more iteration of FWI, the amplitude of the data residual decreases. This implies that the updated model is more similar to the true model.

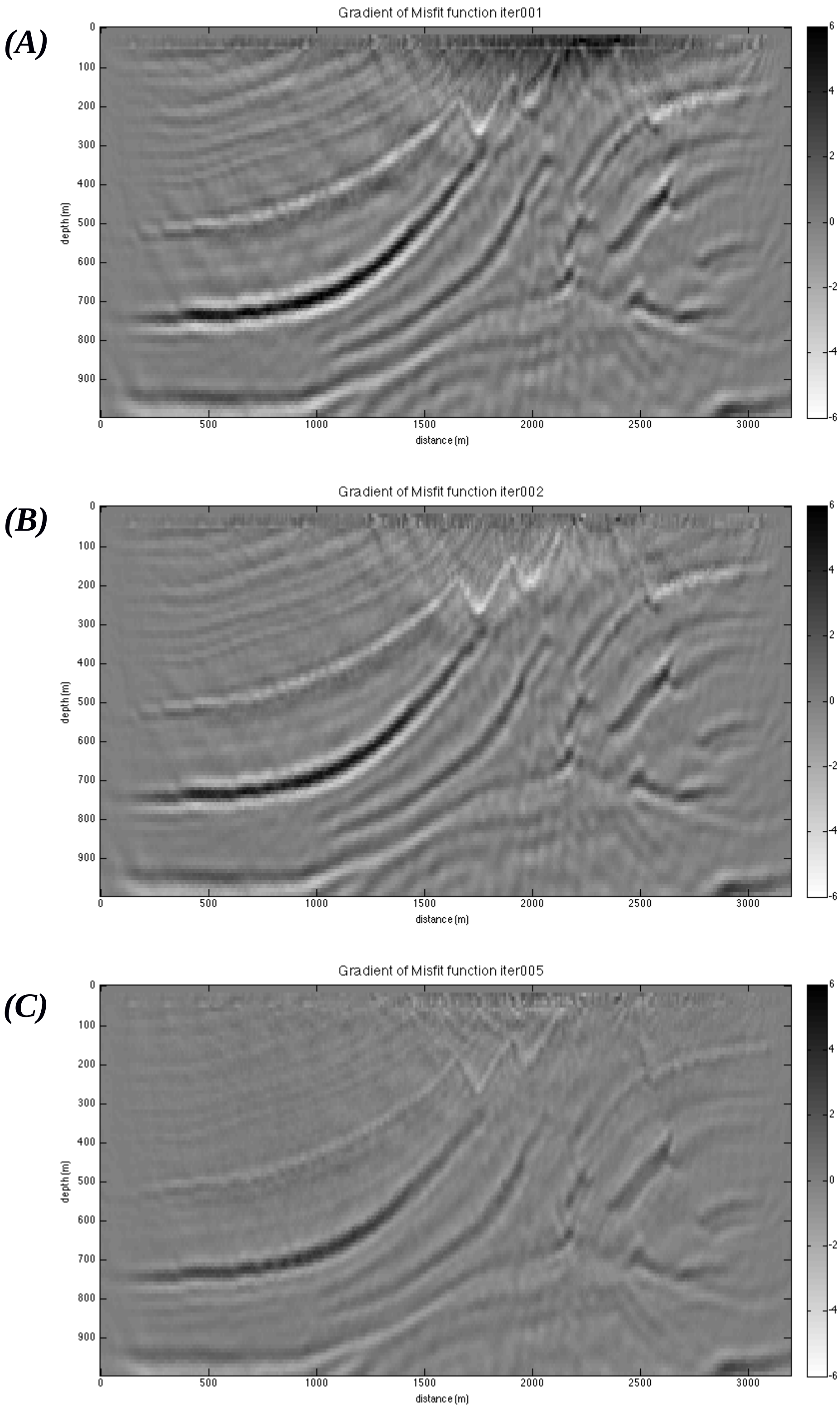

Figure 4.4 the gradient of misfit function calculation (A) from iteration 01, (B) from iteration 02 and (C) from iteration 05

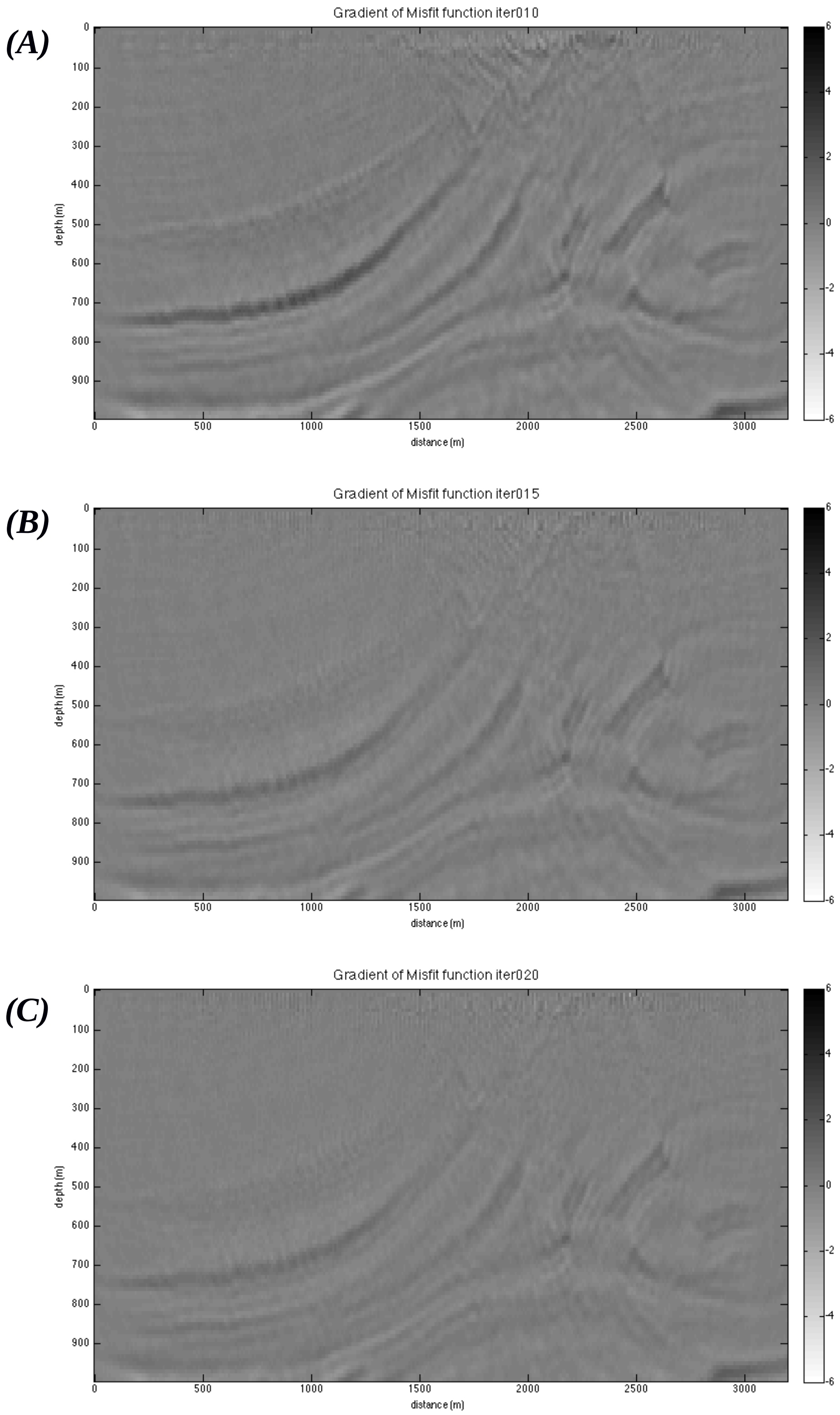

Figure 4.5 the gradient of misfit function calculation (A) from iteration 10, (B) from iteration 15 and (C) from iteration 20

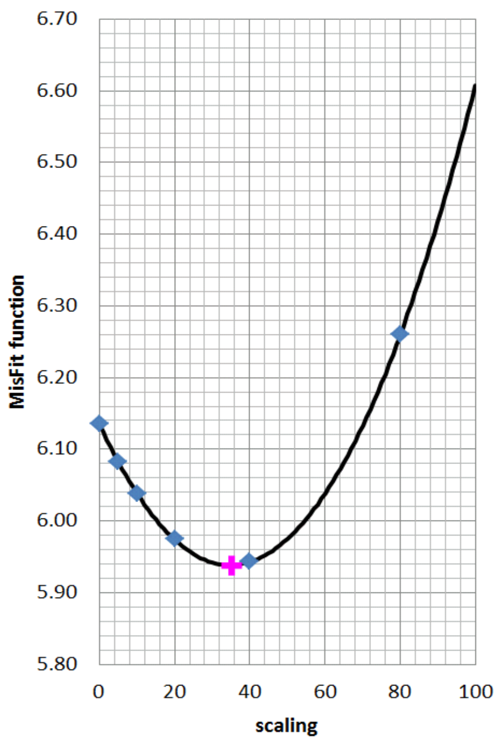

Figure 4.6 example of scale searching for calculates model perturbation. The estimating is searching for the scale that minimise the misfit function calculated from 9 sample shot gathers

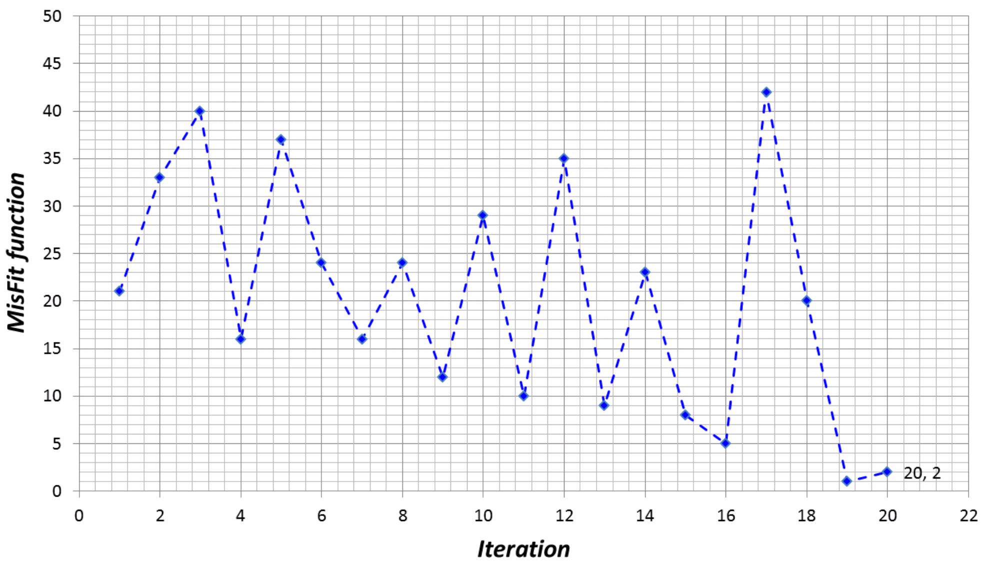

Figure 4.7 plot of the scaling used to calculate the model perturbation on different iteration.

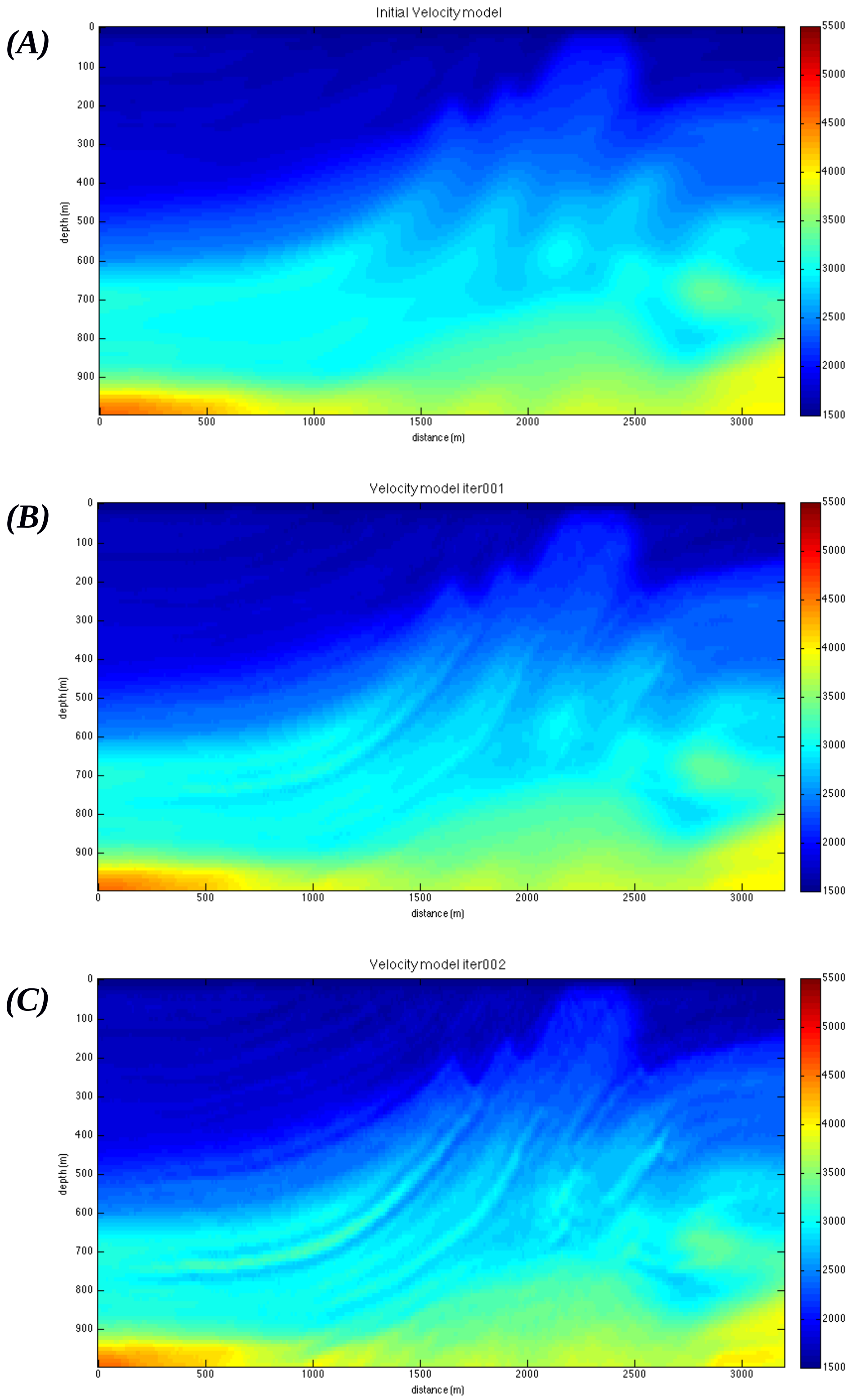

Figure 4.8 (A) the initial velocity model, the recovered velocity model from (B) iteration 001, and (C) iteration 002

(A)

(B)

(C)

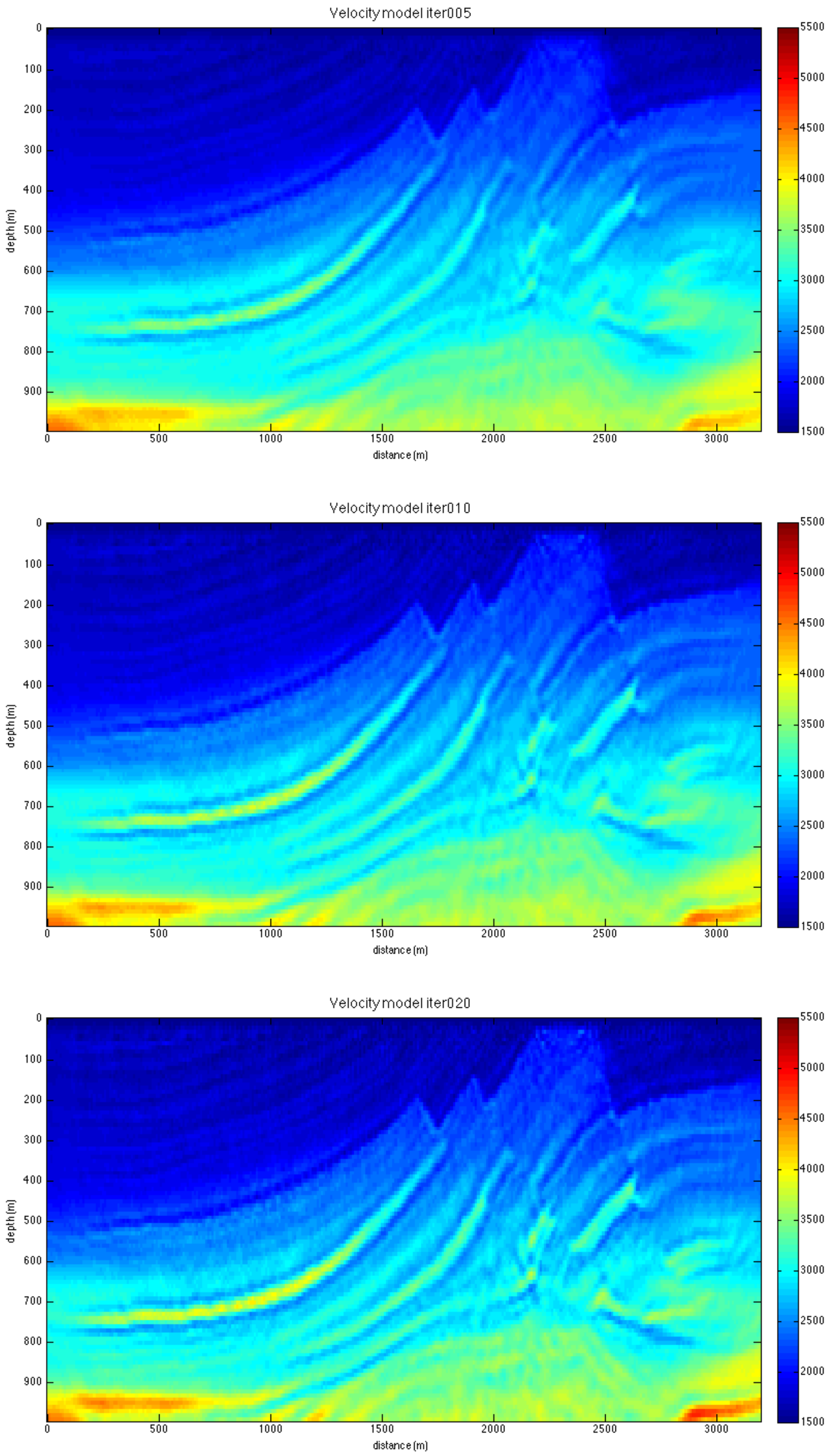

Figure 4.9 the recovered velocity model from (A) iteration 005, (B) iteration 010 and (C) iteration 020.

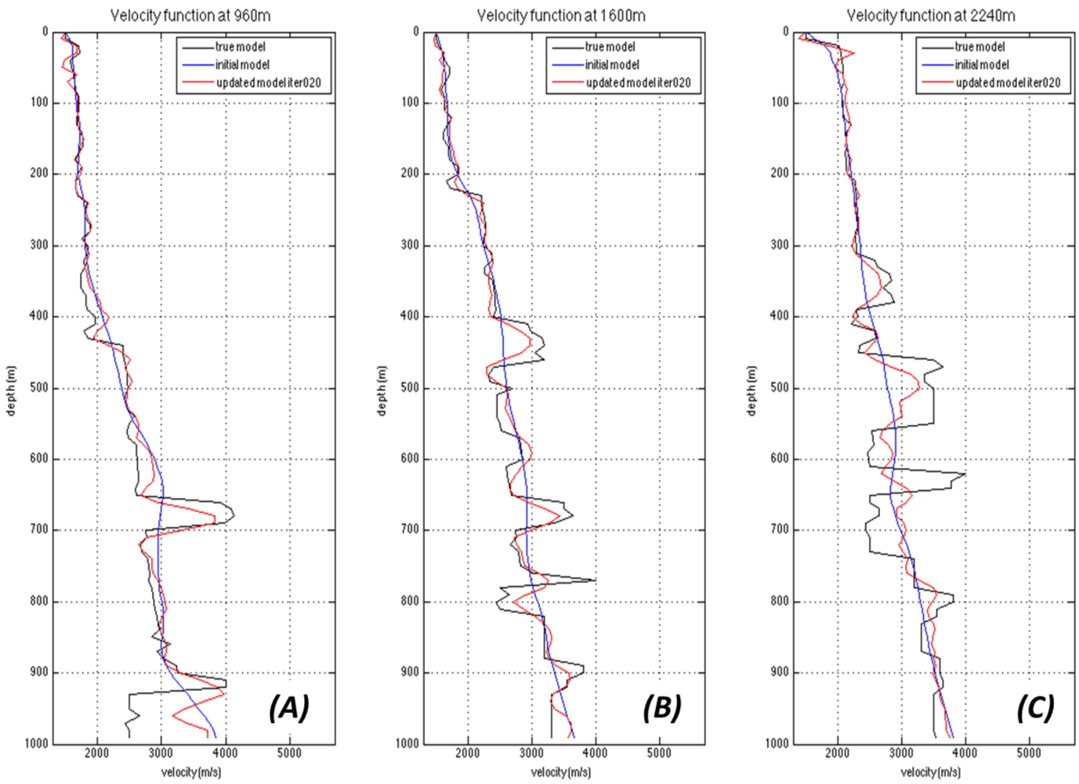

Figure 4.10 comparing between true velocity model (black), initial velocity model (blue) and updated velocity model from iteration 020 at distance (A) 960m, (B) 1600m and (C) 2240m

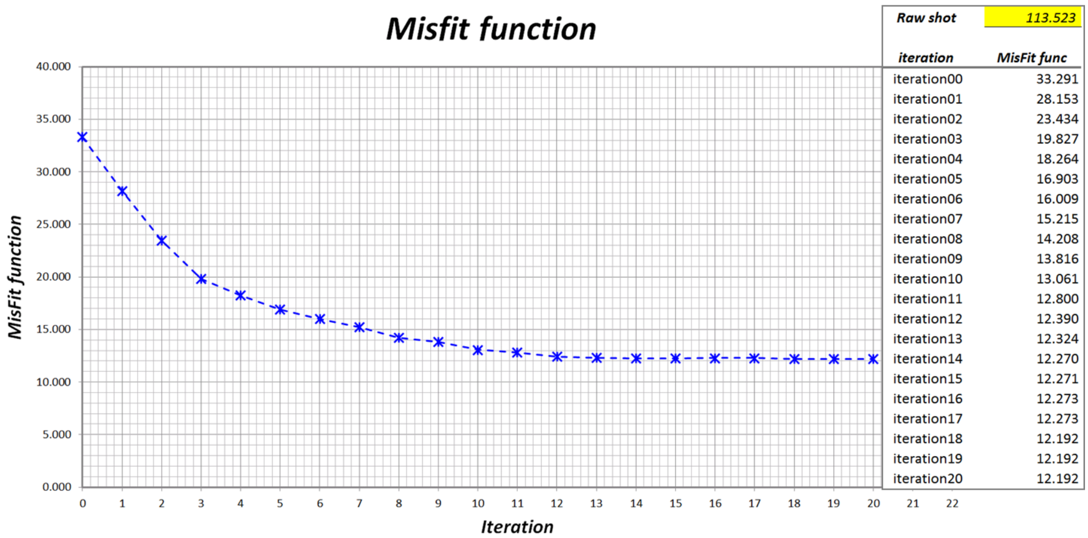

Figure 4.11 misfit function plots with respect to iterations of the inversion.

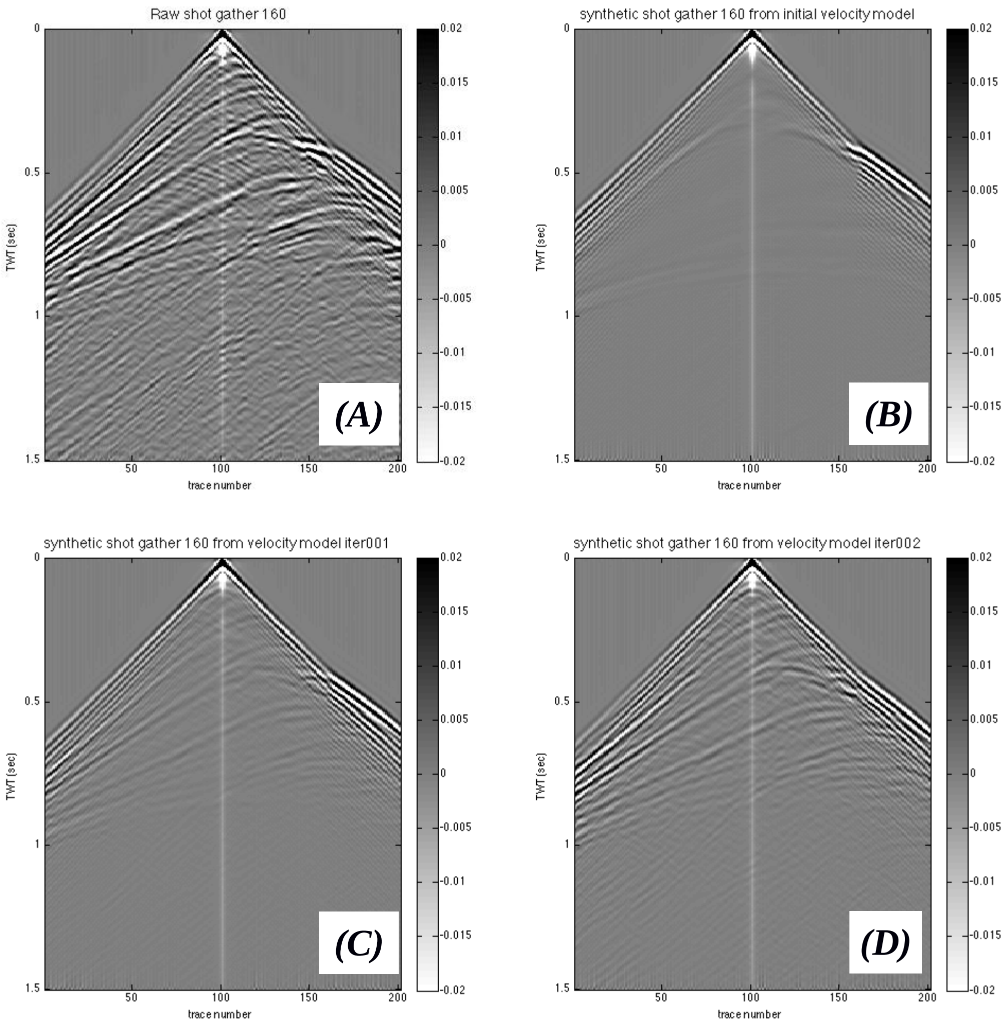

Figure 4.12 synthetic shot gather 160 generated from (A) true velocity model, (B) initial velocity model, (C) updated velocity model iteration001 and (D) updated velocity model iteration002.

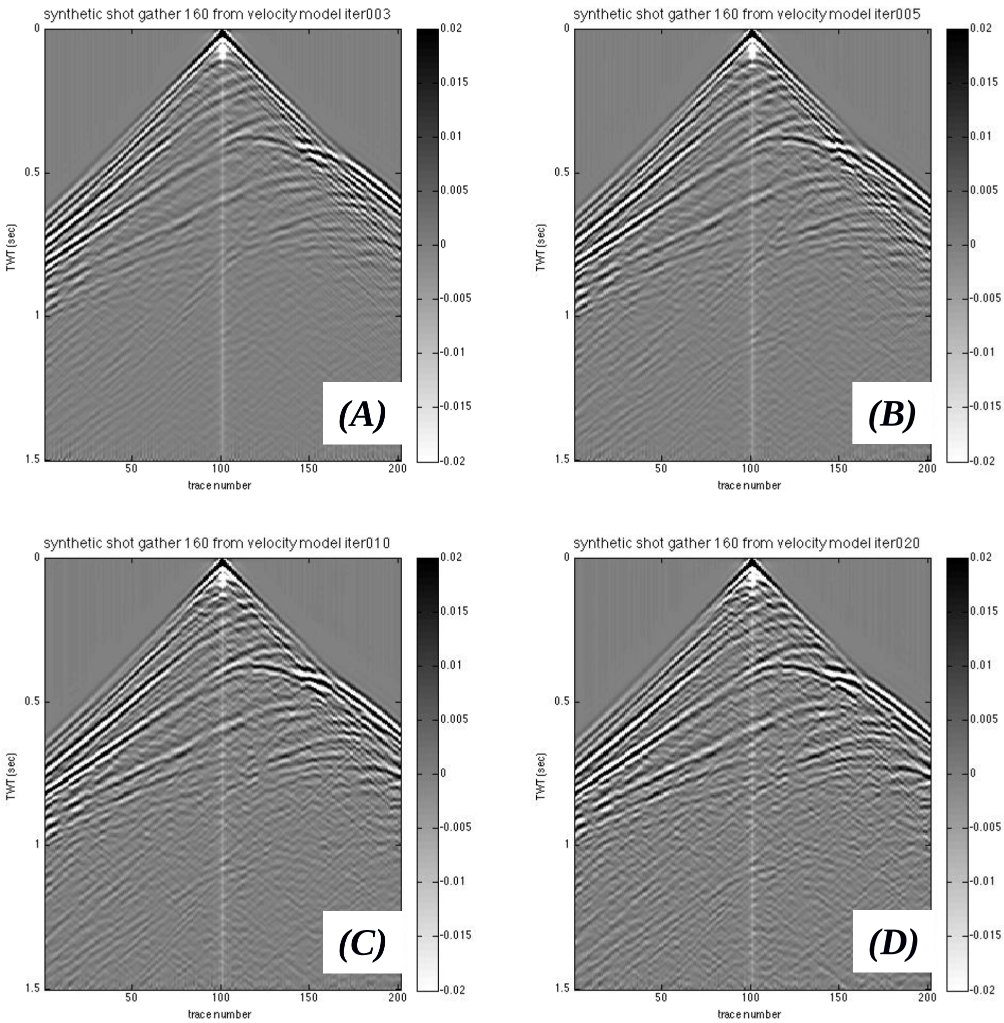

Figure 4.13 synthetic shot gather 160 generated from (A) updated velocity model iteration003, (B) updated velocity model iteration005, (C) updated velocity model iteration010 and (D) updated velocity model iteration020.

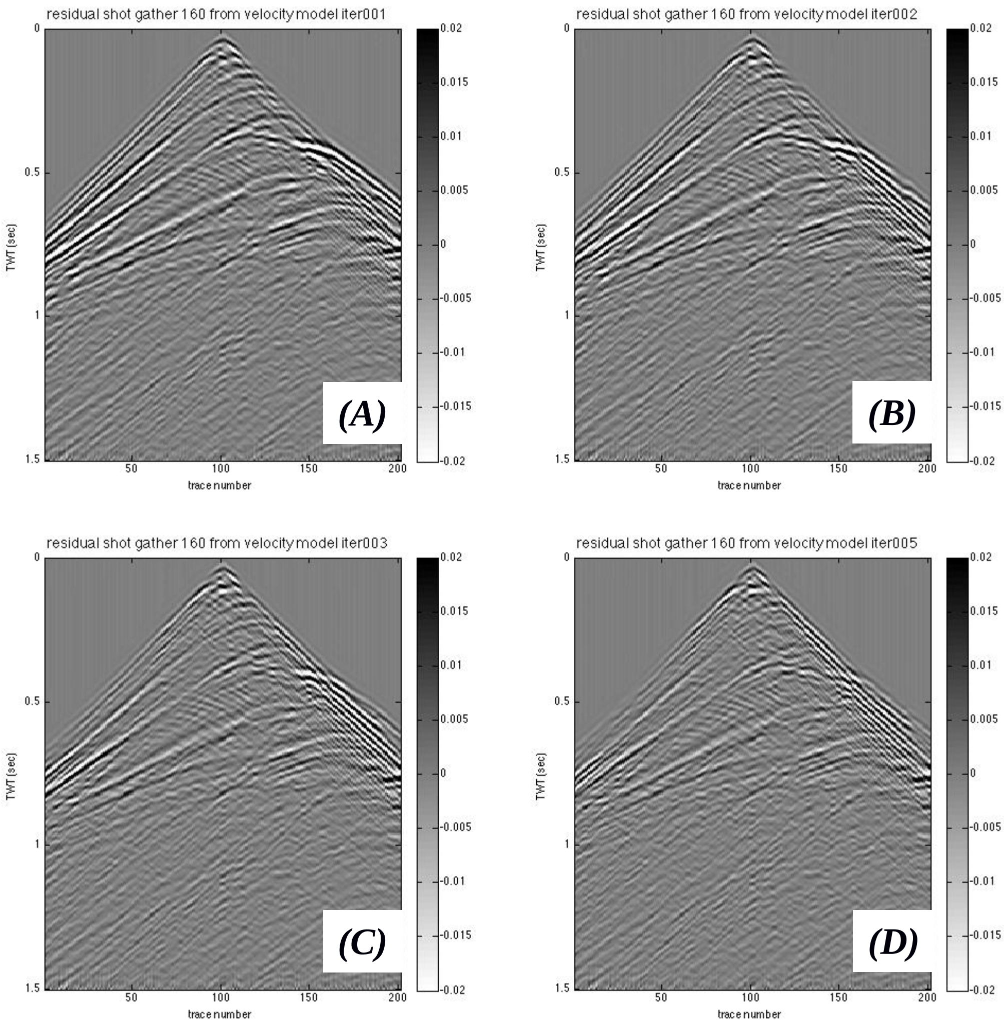

Figure 4.14 residual data from (A) updated velocity model iteration001, (B) updated velocity model iteration002, (C) updated velocity model iteration003, and (D) updated velocity model iteration005

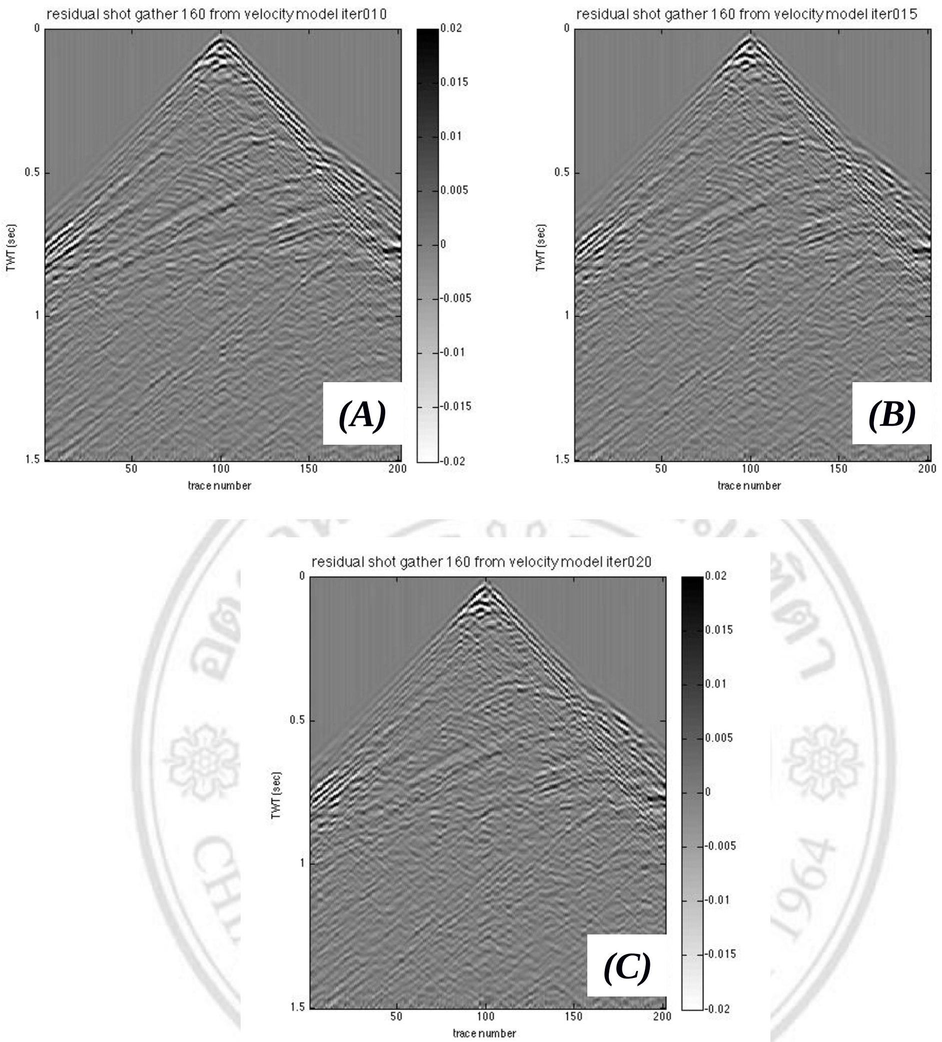

Figure 4.15 residual data from (A) updated velocity model iteration010, (B) updated velocity model iteration015, and (C) updated velocity model iteration020

4.2 Discussion

The synthetic example in the previous section demonstrates that the FWI can be used to update the velocity model. The result shows that after several iterations the velocity model is improved and becomes similar to the true model. However, there are some problems and limitation of FWI has been observed and need to be discussed.

4.2.1 Estimation of scaling

This study used a constant scaling to calculate the perturbation model from the global gradient of misfit function. The scaling is used to determine how much the velocity can change on each of the iterative inversion. Unfortunately, up to some point, the FWI algorithm cannot find a constant scaling that can reduce the misfit function. The decreasing trend towards zero observed in figure 4.7 for scaling used for calculate perturbation model on each of inversion. It means that after some point, with a constant scaling it cannot effectively update the velocity model because the scaling is close to zero and it makes the perturbation model become close to zero as well. However, when considering the gradient of misfit function after 20^{th} iteration, the remaining amplitude can be observed in the deeper part of the section, which could then be used to update the velocity model. Since the amplitude of this gradient of misfit function is very small, the scaling supposed to be high value for the perturbation model.

The difference between the true model and final updated model at offset 1600m, i.e. the residual model, overlain with the perturbation model calculated from the gradient of misfit function with different scaling as shown in Figure 4.16. The result indicates that with higher scaling, the perturbation model can compensate the velocity on the deeper part and better match with the residual model. However, with higher scaling, it introduces the spiking of the velocity on the shallow part, especially above 100m when calculated perturbation model. Therefore, by updating the model with high scaling value, it will be overestimate the perturbation model on the shallow part and increase the misfit function when updated to the new model.

To overcome this limitation, the depth variation scaling or some amplitude precondition should be considered when calculating the perturbation model, to be able to observe the effect of the amplitude scaling to the deeper part of the section

4.2.2 Resolution

According to the resolution, FWI can recover details with an accuracy of half of a wavelength (Pratt et al., 1996). Assuming that the average velocity for our model is 3000m/s and the maximum frequency used to create wavelet is 50 Hz then the estimated wavelength for this dataset is around 60m. Therefore, the minimum thickness that FWI can be recover and update velocity is around 30m.

Figure 4.17 compares the true, initial and updated velocity function at distance 1600m. Figure 4.17 (B) and (C) show FWI can be correctly determined top and the bottom boundary of high velocity layer for 60m and 40m thickness. However, for the layer that has thickness less than 30m, (as shown in Figure 4.17(D)), the result demonstrate that FWI can detect the presence of a thin layer, about 10m thick but cannot be determine the correct bottom boundary of that thin layer.

4.2.3 Runtime

As mention in Chapter01, one obstacle of performing FWI is computer power. The computational cost for FWI is proportional to the number of sources or the number of shots. For this study, the FWI was performed using MATLAB with 12 cores Intel® XEON® E5-2643 v2 processer and 64 GB of memory. The model size was 322 by 100 cells with 10m by 10m cell size. 19 shot records were generated along the surface. Each of shot record consists of 201 receivers with 1.5 sec record length and 4ms sampling interval.

Figure 4.18 summarises overall runtime for FWI and compares the time spent on each process from iteration 01 to 05. Figure 4.18 indicates that it take about 14 to 15 hours to finish on iteration of FWI, the most time consuming process for FWI is computation of the gradient of misfit function.

4.2.4 Real data and 2D synthetic data

Comparing the real data and the synthetic data used in this study, the synthetic data was created base on a 2D model without any noise generated and added to the data which is not realistic to the real dataset. Based on just a 2D algorithm, it cannot generate the sideswipe or a feature out of the plane of a seismic section which will occur in the real dataset because real world is a 3D model. These mention problem could be effect to the inversion when calculate the gradient of misfit function and produce inaccurate model. The wavelet estimation is could be another problem for FWI, because in the real dataset there will be an effect by absorption and distortion which can change the shape of the wavelet with time.

4.2.5 Local minima problem

As the FWI algorithm used in this study is based on the gradient method which is calculated the perturbation model from the steepest descent or the gradient of misfit function. The initial model supposed to be reasonably close to the true model to get to the global minima after updating. It is essentially that the initial model needs to contain the low frequency part of the model to avoid cycle-skipping and local minima problem. One way to solve this problem is to update first the low frequency part of the model by apply a low pass filter to the gradient of misfit function and use that to calculated the perturbation model. Figure 4.11, indicated that after 15 iterations the inversion result is not effective and the misfit function is not reduced to zero, imply that the initial model is lacked of a low frequency component of the model and lead the inversion result to local minima problem.

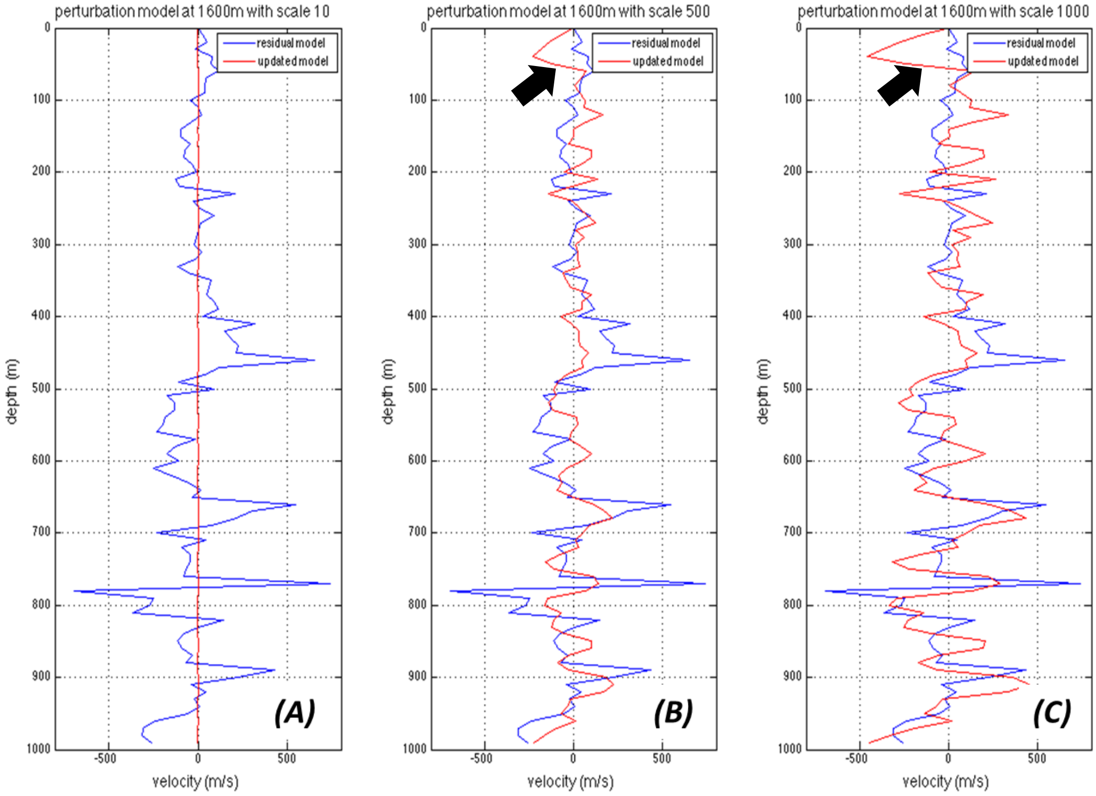

Figure 4.16 the residual velocity model on 20th iteration (blue), compare with perturbation model calculated from gradient of misfit function and (A) with scale 10, (B) with scale 500 and (C) with scale 1000. The arrow indicated the overestimate of the perturbation model with high scaling value.

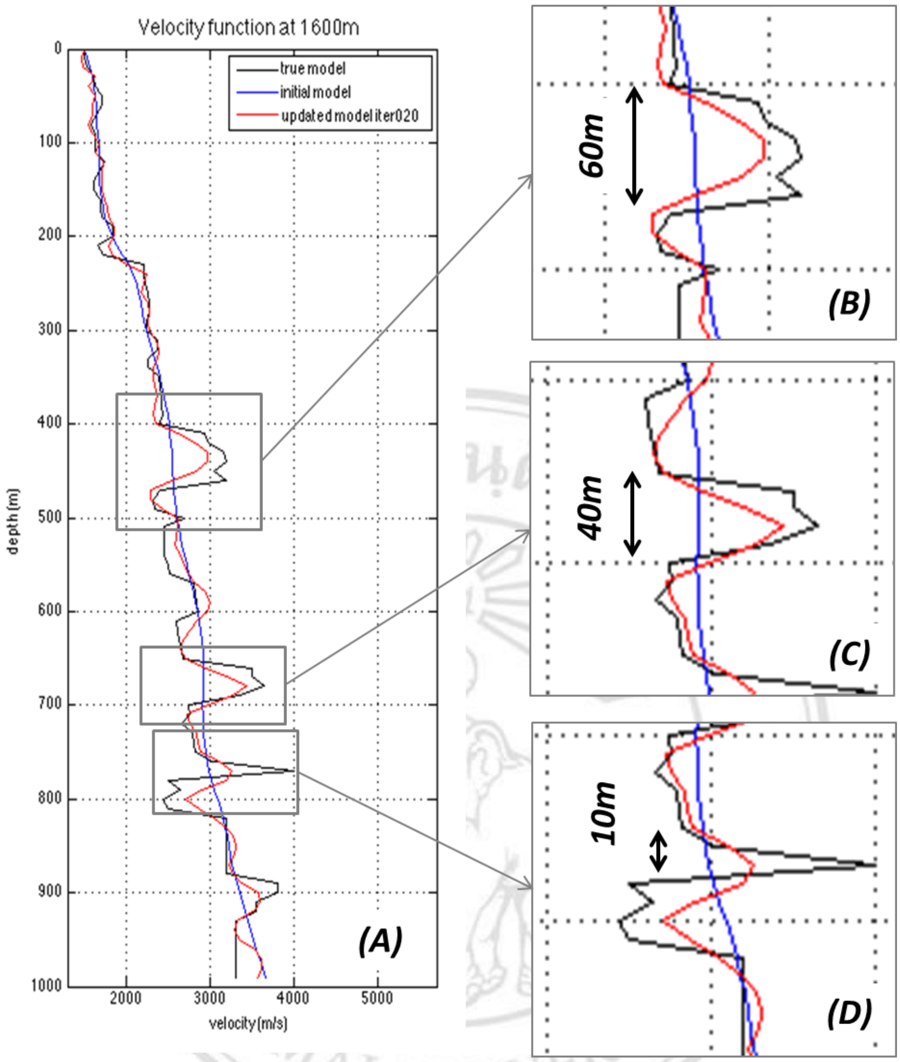

Figure 4.17 comparing the true, initial and final velocity function at 1600m.

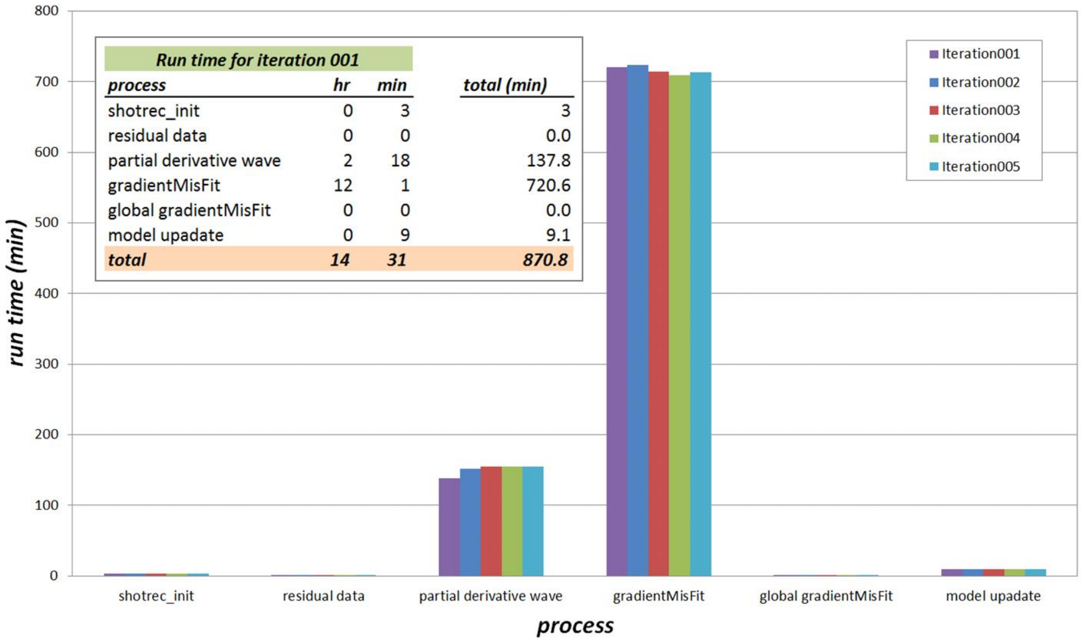

Figure 4.18 compare runtime for each of FWI process from iteration 01 to 05. The table summarises runtime for each of process for iteration 01.