**SÁMUEL MIKOVINY DOCTORAL SCHOOL OF EARTH SCIENCES**

**Theses of Doctoral (PhD) Dissertation**

# ON THE EXAMINATION OF NEAR-SURFACE GEOLOGICAL STRUCTURES THROUGH THE INVERSION OF SEISMIC REFRACTION DATA

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# I.  SCIENTIFIC BACKGROUND AND AIMS

Nowadays besides deep geophysical exploration the near-surface investigation has significance for the solution of geophysical engineering, geotechnical or hydrogeological problems.

The measurement range of geophysical engineering exploration is the uppermost 5-25 m layer of the earth crust. Seismic engineering methods – mainly refraction seismic methods are some of the most effective tools for its exploration, definition of geological layers and their physical parameters besides geomagnetic, geoelectric and gravitational methods (Ádám 1984). In seismic refraction methods the aim is the determination of the velocity structure. Applying the appropriate geophones P- and S-wave velocities can be estimated, and by that several other geological parameters (e.g. Young modulus, Poisson ratio) can be calculated.

In my doctoral studies I examine the near-surface geological structures with seismic methods. My purpose is to give solutions for problems occurring during field measurements and in the forward and inverse seismic refraction problems.

Our experiences gained during the seismic investigation of near surface structures have shown that the accuracy of the exact trigger time has great importance (Sun 2000; Martino, Scarascia Mugnozza 2005). This mainly causes problems in field measurements solving engineering geophysical, geotechnical problems, when the investigated depth is only a few meters. In these cases the highest registered traveltimes are around 40-50 ms compared to it the 1-3 ms trigger error is significant. The inaccuracy of the trigger time can cause evaluation problems that have not been studied before. Therefore, for the elimination of this problem, it was my aim to develop new evaluation procedures and inversion methods using traveltime differences. The idea of traveltime differences is originated from Dobróka et al. (1992).

In the field of refraction seismics usually two-layered models are evaluated in the inversion process. However in multilayered cases the problem of ambiguity can be experienced that has not been investigated earlier. In my PhD studies one of my aims was to investigate this problem with the series expansion based (Dobróka 1994) refraction inversion method developed in the Department of Geophysics of the University of Miskolc (Ormos 2002). I examined the limits and reliability of the method and I found solution for the ambiguity question that arose during the evaluation of datasets measured above laterally changing multilayered geological structures.

My further aim was to make the series expansion based refraction inversion insensitive to the trigger error. For this reason I have inserted the so-called 'iterative traveltime difference algorithm' into the series expansion based refraction inversion algorithm. Therefore I created a new inversion technique that is less sensitive to trigger error and that is capable of evaluating datasets measured above two-dimensional structures.

## II.  DESCRIPTION OF RESEARCH WORK

In my PhD dissertation firstly I give a short literary outline of near-surface seismics; seismic refraction methods in more details. Then I present the most frequently used inversion techniques for the evaluation of geophysical datasets. In the third part of the theoretical introduction I highlight the seismic refraction measurement error that was barely studied before.

I present this trigger error with analytical derivations and as a result I present numerical correlations among the quantity of the trigger error, the parameter values and the estimation error of each parameter. As a result of this analytical examination I also developed two new inversion methods for the elimination of the trigger error. Using these methods the calculations are performed with traveltime differences instead of the measured full traveltime data. As the inverse problem is overdetermined and well-conditioned, I applied the Damped Least Squares method for developing the inversion algorithms. In the so-called 'exact traveltime difference algorithm' a traveltime difference dataset is created from the measured dataset. Properly chosen reference geophones are used for this purpose and the measured dataset is corrected with the reference traveltimes. In the inversion procedure a difference Jacobi's matrix is produced from the original Jacobi's matrix by subtracting the reference geophones' matrix lines from all the other matrix lines connected to the same source point. Therefore the method gives a mathematically exact solution however an essential change has to be performed on the original refraction inversion technique (as every newly calculated data is related to two rays instead of one).It was necessary to develop an inversion method that applies traveltime differences but the inversion algorithm remains as the one that uses full traveltime data. This method is called 'iterative traveltime difference algorithm' as the inversion is solved in two cycles embedded into one another. A traveltime difference dataset is created from the measured one and it is added together with the reference traveltimes calculated on the actual model. A new 'measured dataset' is calculated in each outer iteration step. The traveltimes calculated on the new model are compared to the new 'measured dataset' in the inner cycle. Both new traveltime difference refraction inversion methods were tested on synthetic datasets where the random noise (with Gaussian distribution), the trigger error and the impact of the initial model distance were studied.

In the following chapters of my PhD thesis I examined the resolution characteristics and reliability of the series expansion based refraction inversion method developed in the Department of Geophysics of the University of Miskolc. I present the results of my investigations on synthetic and field datasets, revealing the limitations and reliability of the method.

During the investigation of the series expansion based refraction inversion I examined a relatively barely studied problem: the problem of ambiguity. In this kinematic multilayer refraction inversion method the ambiguity problem can arise because all the propagation velocity and layer thickness parameters may vary laterally along the section and these parameters are described by continuous basis functions expanded in series. For the solution of this problem, besides the application of optimal number of coefficients – successfully used by

Gyulai et al. (2010) – I give two possibilities: the ambiguous parameters has to be estimated with functions expanded in series with significantly different lengths or the estimation has to be done with different basis functions expanded in series for the ambiguous parameters. Both methods were successfully tested on synthetic and field datasets as well.

In the last part of my thesis I embedded the traveltime difference refraction inversion algorithm into the series expansion based refraction inversion method, therefore creating a new inversion method for the evaluation of seismic refraction data measured above 2D geological structures. With this new method the impact of trigger error can be highly reduced and we can evaluate datasets measured above laterally varying two-dimensional geological structures. Similarly to my earlier studies, this method was also tested with synthetic and field datasets as well.

## III.   NEW SCIENTIFIC RESULTS

**Thesis Statement 1**

I analytically examined the effect of surface seismic refraction measurement trigger error for two-layered, one-dimensional geological structures concerning the calculated velocities and layer thicknesses. As a result of this analytical derivation I gave the values of $v_1^{(ih)}$(Eq.1) and $h^{(ih)}$ (Eq.2) that mean the erroneously defined $v_1$ and $h$ parameters resulted from the general evaluation of datasets with trigger error. The following statements are resulted from my investigations:

a) As a result of my analytical investigations I determined that in the evaluation of a dataset full of trigger errors in case of a model with smaller layer thickness the $v_1$ parameter can be defined with lower accuracy (Eq.1). Besides, as a result of systematical tests I determined that the defining accuracy of parameter $v_1$ is minimal at a value of $v_2/v_1=\sim1.6$. If their ratio is different from that, this value increases:

$$v_1^{(ih)} = \frac{x^{(cr)}v_1}{x^{(cr)} + t^{(h0)}v_1} = \frac{2hv_1\sqrt{\dfrac{v_2 + v_1}{v_2 - v_1}}}{2h\sqrt{\dfrac{v_2 + v_1}{v_2 - v_1}} + t^{(h0)}v_1} = \frac{v_1\sqrt{\dfrac{\lambda + 1}{\lambda - 1}}}{\sqrt{\dfrac{\lambda + 1}{\lambda - 1}} + \dfrac{t^{(h0)}v_1}{2h}} , \qquad (1)$$

b) As a result of my analytical investigations I determined that in the evaluation of a dataset full of trigger errors, the higher the ratio of $v_2/v_1$ the lower is the defining accuracy of parameter $h$ (Eq.2):

$$h^{(ih)} = \frac{2h\sqrt{\dfrac{1}{v_1^2} - \dfrac{1}{v_2^2}} + t^{(h0)}}{2\sqrt{\dfrac{1}{v_1^2} - \dfrac{1}{v_2^2} + \dfrac{t^{(h0)2}}{4h^2\dfrac{v_2+v_1}{v_2-v_1}} + \dfrac{t^{(h0)}}{v_1 h\sqrt{\dfrac{v_2+v_1}{v_2-v_1}}}}} \; . \tag{2}$$

**Thesis Statement 2**

For the elimination of trigger error I developed two new algorithms that are capable of evaluating multilayered, one-dimensional geological structures. These methods are the so-called 'exact traveltime difference' and the so-called 'iterative traveltime difference inversion methods'. I examined the effect of trigger error using synthetic datasets with noise of Gaussian distribution.

a) The so-called 'exact traveltime difference inversion method' gives a mathematically exact solution. I developed a totally different inversion algorithm for this purpose compared to the solution using full traveltimes. The method calculates with traveltime differences and difference Jacobi's matrices. I proved that applying the so-called 'exact traveltime difference method' the effect of trigger error can be eliminated and the results are reliable.

b) In the so-called 'iterative traveltime difference inversion method' the estimation is fulfilled in two iteration cycles embedded into each other. During the process of Jacobi's matrices calculation I use full traveltimes. I proved that with this method the effect of trigger error can be eliminated and the results are reliable.

**Thesis Statement 3**

As a result of my investigations concerning the reliability and applicability of the series expansion based refraction inversion method - developed in the Department of Geophysics of the University of Miskolc - I determined that the method is applicable on laterally 'quickly changing' geological structures in an extent that is acceptable in the engineering practice. The results of my synthetic tests confirmed that according to the examined model the results are usable in engineering practice (the relative model distance is below 5%) if the lateral change of layer thickness is approximately one order of magnitude smaller than the lateral change of the structure.

**Thesis Statement 4**

I solved the problem of ambiguity – arisen during the application of the series expansion based refraction inversion method – in two different ways. I defined the parameters and series expansion coefficients causing ambiguity. For the solution I proposed two possible solutions - besides the application of optimal number of coefficients (Gyulai et al. 2010). I confirmed my propositions with synthetic examination results.

a) In the evaluation of two-dimensional, three-layered geological structures I decreased the level of ambiguity by describing the ambiguous parameters with different number of series expansion coefficients but the same basis function (Fourier series). I tested the proposed method on synthetic and field datasets as well.

b) In the evaluation of two-dimensional, three-layered geological structures I decreased the level of ambiguity by describing the ambiguous parameters with series expansion of different basis functions (Fourier series and trigonometric series). I tested the proposed method on synthetic and field datasets as well.

**Thesis Statement 5**

I created a new traveltime difference series expansion based inversion method by combining the iterative traveltime difference algorithm (presented in thesis 2.b) and the series expansion based refraction inversion method. The series expansion coefficients are estimated in the inversion process instead of the parameters. Throughout my investigations I proved that the new method is successfully applicable for the evaluation of datasets full of trigger error, measured above two-dimensional, laterally changing geological structures. The results have reliability appropriate for engineering practice.

I successfully tested the new method on differently erroneous synthetic datasets and field datasets as well.

**PRACTICAL APPLICATION OF THE RESULTS**

In my PhD dissertation I investigated the near-surface refraction seismic methods. The problems arising during measurement and evaluation have great importance in practice.

The newly developed refraction inversion methods can be successfully applied in the geophysical and engineering practice if trigger error exists in the measured dataset. It is especially significant if the measurement was fulfilled on hard geophysical site or in bad conditions and the poor quality measurement cannot be repeated. In such cases the dataset can only be qualitatively improved during processing and evaluation. The above presented developments have significance also in the process and evaluation of well-bore acoustic datasets.

A possible way for the further development of these methods is the introduction of new basis functions into the series expansion based inversion method and the estimation of additional physical parameters (geophysical terrain, elasticity modulus, etc.) in the inversion process.

**LIST OF PUBLICATIONS REFERRED IN THE TEXT**

Ádám, O., 1984: Szeizmikus kutatás. Kézirat. Nehézipari Műszaki Egyetem, Bányamérnöki Kar, Tankönyvkiadó, Budapest, 472 p.

Dobróka, M., 1994: Változó rétegvastagságú inhomogén szeizmikus hullámvezetőben terjedő Love-típusú hullámok diszperziós relációja; Az abszorpciós-diszperziós jellemzők inverziója. Doktori értekezés, Miskolc.

Dobróka, M., Dresen, L., Gelbke, C., Rüter, H., 1992: Tomographic inversion of normalized data: double-trace tomography algorithms. Geophysical Prospecting, Vol. 40, pp 1-14.

Gyulai Á., Ormos T., Dobróka M., 2010: A quick 2-D geoelectric inversion method using series expansion. Journal of Applied Geophysics, 72, pp 232-241.

Martino, S., Scarascia Mugnozza, G., 2005: The role of the seismic trigger in the Calitri landslide (Italy): historical reconstruction and dynamic analysis. Soil Dynamics and Earthquake Engineering, Vol. 25, pp 933-950.

Ormos, T., 2002: Inversion of Refracted Travel-times for Near-surface Investigation. EAGE 64th Conference and Exhibition, Extended Abstract, D025.

Sun, R. 2000: Trigger Time Synchronization in Shallow Seismic Exploration. TAO, Vol. 11(2), pp 381-392.

## IV. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

**JOURNAL PUBLICATIONS**

1. PARIPÁS,A.N., ORMOS, T. 2013: New inversion techniques for the elimination of trigger errors in seismic refraction data. *Geosciences and Engineering*. Vol.2(3), pp. 73-82.HU ISSN 2063-6997

2. ORMOS, T., PARIPÁS, A.N. 2012: Traveltime differences in seismic refraction inversion. *Geosciences and Engineering*. Vol.1(2) pp 123-128.HU ISSN 2063-6997

3. PARIPÁS, A.N., ORMOS, T. 2012: Resolution and ambiguity studies for a series expansion based multilayer refraction inversion method. *Acta Geodaetica et Geophysica Hungarica,* Vol. 47(2), pp. 197-209. DOI: 10.1556/AGeod.47.2012.2.8. IF: 0.346.

4. PARIPÁS, A.N., ORMOS, T. 2012: Refrakciós SH hullámbeérkezések sorfejtéses inverziója. *Magyar Geofizika,* 52(4) pp. 185-192.HU ISSN 0025-0120

**INTERNATIONAL CONFERENCE EXTENDED ABSTRACTS**

1. PARIPÁS, A.N., SOMOGYI MOLNÁR, J., ORMOS, T., PETHŐ, G. 2012: Inversion of refracted first breaks using traveltime differences. Near Surface Geoscience 2012, Proceedings, Paris, France, 2012.09.02-05. P50. pp. 1-4.

2.   PARIPÁS, A.N. 2012: The application of traveltime differences in the inversion of refracted first breaks. 8th International Conference of PhD Students, Miskolc, 2012.08.05-11. pp. 1-6. (ISBN: 978-963-661-994-7)

3.   PARIPÁS, A.N., ORMOS, T. 2011: Inversion of First Breaks on Multilayered Media. 6[th]Congress of Balkan Geophysical Society, Budapest, Conference Proceedings, 2011.10.03-06. B1. pp 1-4. (ISBN 978-90-73834-16-3)

4.   PARIPÁS, A.N., ORMOS, T. 2011: Ambiguity Question in Kinematic Multilayer Refraction Inversion. Near Surface 2011 – 17[th]European Meeting of Environmental and Engineering Geophysics, Leicester, United Kingdom, Conference Proceedings, 12-14.09.2011. P13. pp 1-4. (ISBN 978-90-73834-15-6)

5.   PARIPÁS, A.N., ORMOS, T. 2011: Investigating the Problem of Equivalence in Kinematic Refraction Inversion. XXV. microCAD International Scientific Conference, Section B, Proceedings, Miskolc, 31.03–01.04.2011. pp 29-34. (ISBN 978-963-661-955-8)

6.   PARIPÁS, A.N., ORMOS, T. 2010: Investigations on Kinematic Refraction Inversion at Different Geological Models. Near Surface 2010 - 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland, Conference Proceedings, 6-8.09.2010. P52, pp 1-4. (ISBN 978-90-73781-88-7)

7.   PARIPÁS, A.N. 2010: Solution of a Refraction Inverse Problem Using Field Data Measured in the Telkibánya Region. 7th International Conference of PhD Students, Section F, Proceedings, Miskolc, 8-13.08.2010. pp 61-66. (ISBN 978-963-661-941-1)

8.   PARIPÁS, A.N. 2010: Examination of a Refraction Inverse Problem On Different Geological Models. XXIV. microCAD International Scientific Conference, Section B, Proceedings, Miskolc, 18-20.03.2010. pp 13-18. (ISBN 978-963-661-907-7)

**DOMESTIC CONFERENCE PRESENTATIONS**

1.   PARIPÁS, A.N., ORMOS T. 2012: Traveltime differences in seismic refraction inversion. Conference & Exhibition on Earth Sciences and Environmental Protection, Miskolc, 2012.09.27-29.

2.   PARIPÁS, A.N. 2011: Többréteges szerkezetek refrakciós sorfejtéses inverziója. Doktoranduszok Fóruma, Műszaki Földtudományi Kar Szekciókiadványa, Miskolc, 2011.11.08. pp 65-72.

3.   PARIPÁS, A.N. 2011: A Study on a Problem of Equivalence in Kinematic Refraction Inversion. XLII. Meeting of Young Geoscientists, Győr, 25-26.03.2011. p

4.   PARIPÁS, A.N. 2010: Investigation of a Refraction Inverse Problem on Different Geological Models. XLI. Meeting of Young Geoscientists, Mátrafüred, Proceedings, 26-27.03.2010. p 30.

5.  PARIPÁS, A.N. 2009: Szeizmikus előremodellezés véges különbséges módszerrel. Doktoranduszok Fóruma, Műszaki Földtudományi Kar Szekciókiadványa, Miskolc, 2009. november 5. pp 88-93.

**INTERNATIONAL CONFERENCE PRESENTATIONS**

1.  PARIPÁS, A.N., ORMOS, T. 2012: Traveltime differences in seismic refraction inversion. Conference & Exhibition on Earth Sciences and Environmental Protection, Miskolc, 2012.09.27-29.

2.  PARIPÁS, A.N., SOMOGYI MOLNÁR, J., ORMOS, T., PETHŐ, G. 2012: Inversion of refracted first breaks using traveltime differences. Near Surface Geoscience 2012, Proceedings, Paris, France, 2012.09.02-05. P50.

3.  PARIPÁS, A.N. 2012: The application of traveltime differences in the inversion of refracted first breaks. 8th InternationConference of PhD Students, Miskolc, 2012.08.05-11.

4.  PARIPÁS, A.N., ORMOS, T. 2011: Inversion of First Breaks on Multilayered Media. 6th Congress of Balkan Geophysical Society, Budapest, Conference Proceedings, 2011.10.03-06. B1.

5.  PARIPÁS, A.N., ORMOS, T. 2011: Ambiguity Question in Kinematic Multilayer Refraction Inversion. Near Surface 2011 – 17th European Meeting of Environmental and Engineering Geophysics, Leicester, United Kingdom, Conference Proceedings, 12-14.09.2011. P13.

6.  PARIPÁS, A.N., ORMOS, T. 2011: Investigating the Problem of Equivalence in Kinematic Refraction Inversion. XXV. microCAD International Scientific Conference, Section B, Proceedings, Miskolc, 31.03–01.04.2011.

7.  PARIPÁS, A.N., ORMOS, T. 2010: Investigations on Kinematic Refraction Inversion at Different Geological Models. Near Surface 2010 - 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland, Conference Proceedings, 6-8.09.2010. P52.

8.  PARIPÁS, A.N. 2010: Solution of a Refraction Inverse Problem Using Field Data Measured in the Telkibánya Region. 7th International Conference of PhD Students, Section F, Proceedings, Miskolc, 8-13.08.2010.

9.  PARIPÁS A. N. 2010: Examination of a Refraction Inverse Problem On Different Geological Models. XXIV. microCAD International Scientific Conference, Section B, Proceedings, Miskolc, 18-20.03.2010.

**HUNGARIAN DOMESTIC CONFERENCE PRESENTATIONS**

1.  PARIPÁS, A.N. 2011: Többréteges szerkezetek refrakciós sorfejtéses inverziója. Doktoranduszok Fóruma, Műszaki Földtudományi Kar Szekciókiadványa, Miskolc, 2011.11.08.

2.  PARIPÁS, A.N. 2011: A refrakciós inverz feladat megoldása sorfejtéssel. Inverziós Ankét, Miskolc, 2011.11.07.

3.  PARIPÁS, A.N. 2011: A Study on a Problem of Equivalence in Kinematic Refraction Inversion. XLII. Meeting of Young Geoscientists, Győr, 25-26.03.2011.

4.  PARIPÁS, A.N. 2010: Investigation of a Refraction Inverse Problem on Different Geological Models. XLI. Meeting of Young Geoscientists, Mátrafüred, 26-27.03.2010.

5.  PARIPÁS, A.N. 2009: Véges differenciás modellezés alkalmazása a szeizmikában. Ifjúsági Előadói Nap, Miskolc, 2009.12.11.

6.  PARIPÁS, A.N. 2009: Szeizmikus előremodellezés véges különbséges módszerrel. Doktoranduszok Fóruma, Miskolc, 2009.11.05.