RESEARCH REPORT ON THE RESULTS OF OTKA PROJECT PD-109408

In the framework of the 3 years project (2013–2016), new well-log-analysis methods were developed for improving the petrophysical characterization of shallow structures. The first two phases of the original work plan and the third phase by a modified work plan approved by the president of the college have been completed. The results were published in scientific (including impact factor) journals and presented in both domestic and international conferences. The support of the National Research Development and Innovation Office is indicated in all published papers and conference presentations.

Results of the first year

In the first year, we studied the possibility of using the Csókás method based permeability estimation in shallow boreholes. We studied the scientific literature and performed computer program development in MATLAB for the calculation of the Csókás formula-based permeability and hydraulic conductivity. At first, detailed numerical experiments were made using exactly known petrophysical models to study the accuracy and reliability of permeability estimation. Synthetic data were calculated by solving the forward problem to which different amount of noise was added. The noise sensitivity of permeability estimation was studied using synthetic data contaminated with 0–10 % Gaussian distributed noise. The results of Csókás formula were compared to those of the traditional Kozeny-Carman method. We obtained a good fit between the permeability logs calculated separately by the two methods.

The Csókás method was tested using real data. Two data sets measured in different sedimentary formations were processed to demonstrate the feasibility of the Csókás method. We concluded that the Csókás method yielded satisfactory results in unconsolidated sediments by different amount of noise, which was confirmed by independent deterministic and statistical modeling results (Kormos, 2014; Szabó et al., 2015a). The results were also published in an impact factor journal (Szabó et al., 2015b), in which we put emphasize on the validation of estimation results by core measurements and multivariate statistical analysis of well logs. A set of detailed regression analyses was performed to specify the local regression relation between hydraulic conductivity and shale volume, porosity and specific surface of grains in a thermal water well situated near to Baktalórántháza. We derived the critical velocity of flow from hydraulic conductivity estimated by the Csókás method.

The Csókás method makes use of the relation between the formation factor and effective grain size, which are strongly related to the true resistivity of groundwater formations. To extend the validity of the Csókás formula, the resistivity distribution of the shallow environment must be a priori known. For this purpose, a series expansion-based geoelectric inversion method was developed and applied to two VES profiles in Hungary (Gyulai and Szabó, 2014). On the other hand, permeability estimation highly depends on the probe response equations used in the given formation. A hierarchical cluster analysis technique was applied to separate different lithological units and to calculate the zone parameters included in the response equations (Szabó et al., 2013). The published statistical technique was analogously used in shallow formations. Anett Halmágyi employed in the project used the own-developed clustering software for lithological characterization of carbonate sediments in her MSc thesis. Anett Halmágyi got a special award in the XXXII. National Scientific Student Conference (Halmágyi, 2015).

In order to find an independent solution for permeability estimation, we improved a sonic log based interpretation method. In the literature, we found a statistical approach for calculating permeability from acoustic full-waveform data. In well-log-analysis practice, a linear connection is assumed between Stoneley-wave slowness and permeability of primary porosity rocks. By making synthetic numerical experiments involving homogeneous and inhomogeneous layers and different amount of data noise, we detected a nonlinear empirical connection between the above quantities. We have improved the regression equation and successfully applied it to well-logging data in an Australian hydrocarbon-field (Szabó and Kalmár, 2013a; Szabó and Kalmár, 2013b; Kalmár, 2014). We increased the estimation accuracy significantly compared to the traditional (linear) method in case of real data. This research formed the basis of the MSc thesis of Csilla Kalmár, who was employed in the project. Csilla Kalmár was awarded with second prize in the XXXII. National Scientific Student Conference (Kalmár, 2015b). The nonlinear statistical technique for permeability prediction using Stoneley velocity data was tested on Hungarian oilfield data sets the results of which were presented in a domestic conference organized by the Association of Hungarian Geophysicists (Kalmár, 2015a). In the case studies, we confirmed the validity of the nonlinear approach in domestic hydrocarbon-bearing formations.

Results of the second year

In the second year, a factor analysis based method was developed for the estimation of petrophysical parameters in groundwater formations. We studied the scientific literature and performed computer program development in MATLAB for processing well-logging data sets. We calculated factor logs and performed detailed regression analysis to reveal the correlation relations between the statistical factors and petrophysical properties. Detailed numerical tests were made on synthetic data to prove the feasibility of the factor analysis algorithms. The Geokomplex Ltd. supported the research with domestic well-logging data and core measurements. American data sets were collected by open file reports available on the internet, the permission of using the data was granted by e-mail response.

We applied the method of factor analysis to field data collected from Hungary and the USA. In each case, a strong relation was detected between the first statistical factor and hydraulic conductivity. By revealing the regression relation between the above quantities, we estimated the hydraulic conductivity along the entire length of the borehole. Synthetic modeling experiments and field cases demonstrated the feasibility of the statistical method, which could be applied in both clastic and fractured aquifers (Szabó, 2015a). The results of factor analysis also showed consistence with those of the Kozeny-Carman method. The field results were confirmed by core measurements and pumping test data. The factor versus permeability relation was approximately area-independent, which allowed the extension of the formula to bigger areas and different sedimentary formations. An impact factor article was written on hydrogeological application of the method (Szabó, 2015b), and a conference presentation was delivered (Szabó and Kormos, 2014). A comparative regression study showed that the results of factor analysis were close to those of the Csókás method and core analysis (Szabó et al., 2015c). We specified the options, advantages and disadvantages of using the three methods in the same paper.

The results of factor analysis can be effectively used in inverse modeling. The petrophysical parameters extracted by factor analysis (e.g., shale volume) can be fixed during the inversion process, which increases the overdetermination ratio in the inverse problem and the accuracy of the estimated petrophysical model. To confirm the result of factor analysis in a more reliable way, we developed a global optimization based inversion technique. The increase of the vertical resolution was presented in Szabó and Dobróka (2014), while a cluster analysis assisted inversion estimation of layer-thicknesses and petrophysical parameters were detailed in a book chapter (Dobróka and Szabó, 2015). At the end of the period, we started the development of factor analysis to evaluate the petrophysical properties of shallow unsaturated sediments using engineering geophysical sounding data. The Elgoscar–2000 Ltd. supported the research with domestic data.

Results of the third year

We continued the research with the development of an iterative factor analysis algorithm using Steiner-Cauchy weights, which was applied to engineering geophysical sounding data. Cone resistance, natural gamma-ray intensity, electric resistivity, density and neutron-porosity data acquired by direct-push tools were simultaneously processed to give a robust estimate to well logs of factor variables and water content in shallow heterogeneous formations (Szabó and Balogh, 2015; Balogh, 2016a; Balogh, 2016b; Balogh, 2016c). We performed computer program development in MATLAB to test the method on both synthetic and real data. The statistical procedure is based on the iterative reweighting of data prediction error (i.e., misfit between the measured and calculated data) using the Steiner's most frequent value method, which is famous of its robustness and high statistical efficiency. The new statistical approach improves the result of traditional factor analysis in case of extremely noisy and not normally distributed data sets. By this manner, the factor logs can be calculated more accurately. A strong regression relation was detected between the first factor estimated by Steiner-weighted factor analysis and water content. Numerical tests made on synthetic data showed that at least 30–40 % improvement in accuracy could be reached by the robust factor analysis algorithm. (In case of having more outliers in the data set, even better results can be obtained.) The feasibility of the most frequent value based factor analysis was tested using engineering geophysical sounding logs measured in a Hungarian loessy-sandy unsaturated formation. The estimated values of water content were verified by quality-checked local (depth-by-depth) inversion. We developed a weighted least squares based inversion method to estimate the water content from an independent source. The results of factor analysis showed good agreement with those of local inversion (Szabó and Balogh, 2016).

The weighted algorithm of factor analysis was further developed to multidimensional applications, which allowed the robust estimation of factors and water content along the lateral coordinates, too. We determined the 1D and 2D spatial distributions of water content. The 2D distribution of water (and air) content showed a proper fit to that of interpolated 1D local inverse modeling (Balogh and Szabó, 2016). We further improved the performance of factor analysis using a global optimization method, which reduced the misfit between the measured and calculated (standardized) data. Oilfield well logs were processed to give an estimate to factor logs by using a float-encoded genetic algorithm. We predicted the shale volume and permeability of hydrocarbon formations. A comparative numerical analysis made between the genetic algorithm-based factor analysis procedure and independent well log analysis showed consistent results. The method can be used for the processing of engineering geophysical sounding data. The results were presented in an international reservoir modeling conference (where a limited number of papers had been accepted) and published in the form of a full paper (Szabó, 2016).

Partly based on the results of the second year, we developed a novel inversion method called interval inversion, which significantly reduced the estimation errors of petrophysical parameters (the relative percentage improvement was obtained around 40–50 %). The results were published in GEOPHYSICS (Dobróka et al., 2016), which is one of the most prestigious (Q1 ranked) scientific journal in the current discipline. We found the interval inversion method worth using as a reference method in the factor analysis of engineering geophysical sounding data. We asked a permission from Prof. Dr. Attila Demény to change the original work plan of the third year, which was granted on 16 December 2015. We developed the interval inversion algorithm for the processing of engineering geophysical sounding data and implemented the inversion method in MATLAB. Since these results had not been published before the closing of the project, we give now a short overview of the achieved results.

The local inversion method (solved point-by-point along the penetration hole) conventionally used for the evaluation of soil parameters represents a marginally overdetermined inverse problem, which is rather sensitive to data noises and limited in estimation accuracy. To reduce the estimation errors of inversion unknowns, we implemented the interval inversion method, which inverts all data along the entire length of the drill-hole to estimate the vertical distributions of soil parameters in a joint inversion procedure. The increase of the overdetermination ratio (which is approximately 6 for the interval inversion method and 1.3 for local inversion in case of engineering geophysical soundings) allows a more accurate estimation of inversion unknowns. We extended the validity of probe response functions to the entire depth of the penetration hole. We expanded the model parameters into series by using 40^{th} degree Legendre polynomials as basis functions for modeling inhomogeneous formations. We solved the inverse problem for smaller number of expansion coefficients than data to derive the petrophysical parameters in a stable overdetermined inversion procedure. Numerical tests using engineering geophysical sounding logs measured in a Hungarian loessy-sandy unsaturated formation proved the feasibility of the interval inversion method and most frequent value based factor analysis. The result of interval inversion is illustrated in **Figure 1**. The measured penetration logs are natural gamma-ray intensity (*GR*), bulk density (ρ_b), neutron-porosity (Φ_N) and resistivity (*R*). The estimated soil parameters are water volume (V_w), sand volume (*Vs*) and clay volume (V_{cl}). The air content (V_g) is derived from the inversion results by using the material balance equation. The green shaded area represents the uncertainty of input logs, while the light blue one is the estimation error of soil parameters (σ is the standard deviation of the given parameter). By using the orthonormal Legendre polynomials as basis function, the correlations of the inversion unknowns was reduced to a minimum level. The average of correlation coefficients was 0.08 for expansion coefficients and 0.45 for soil parameters (in local inverse problems normally they are $r \sim 0.6$–0.7). The interval inversion gave accurate and reliable results.

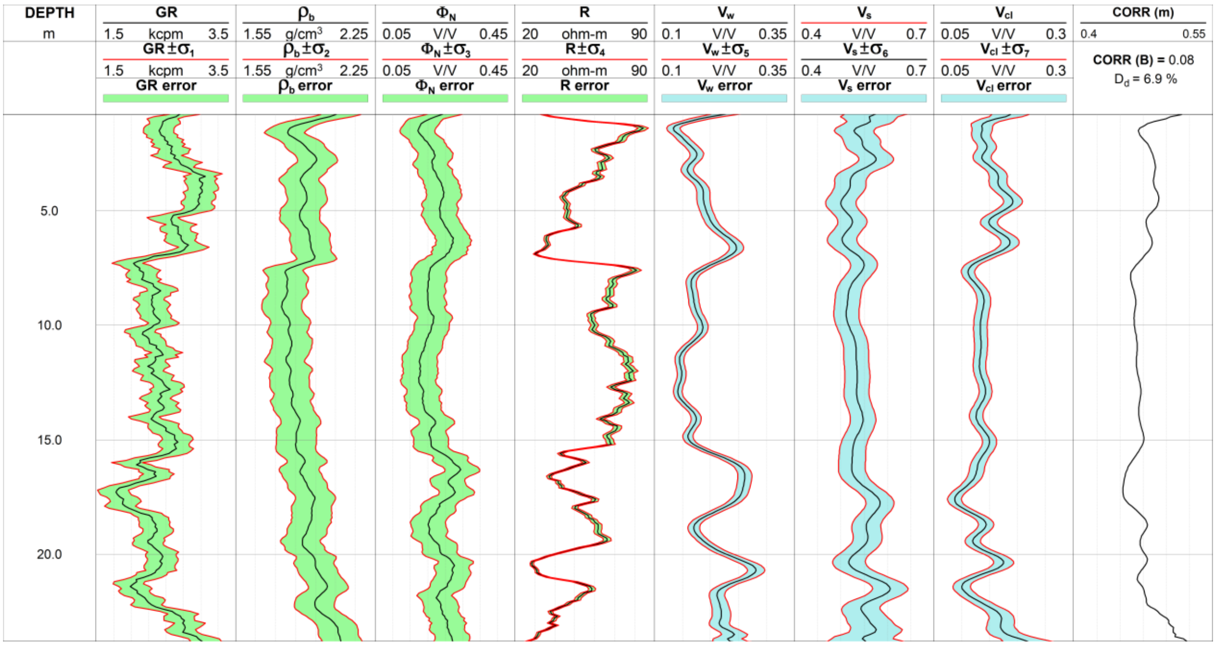

Figure 1. Interval inversion of engineering geophysical sounding data

We calculated the water volume separately by interval inversion and most frequent value based factor analysis. In factor analysis, the solution was weighted according to the deviation between the observed and predicted data. Moreover, the well log types were also weighted differently and the scale parameter (dihesion) of the Steiner's weighting process was optimized automatically (**Figure 2**). It can be seen that big deviations give small weights and vica versa. By the analysis of factor loadings, we showed the strongest correlation between the first factor and saturation sensitive logs such as Φ_N and R. For the regression tests, water volume was given a priori from the interval inversion procedure. The results of factor analysis and interval inversion showed a good agreement (**Figure 3**).

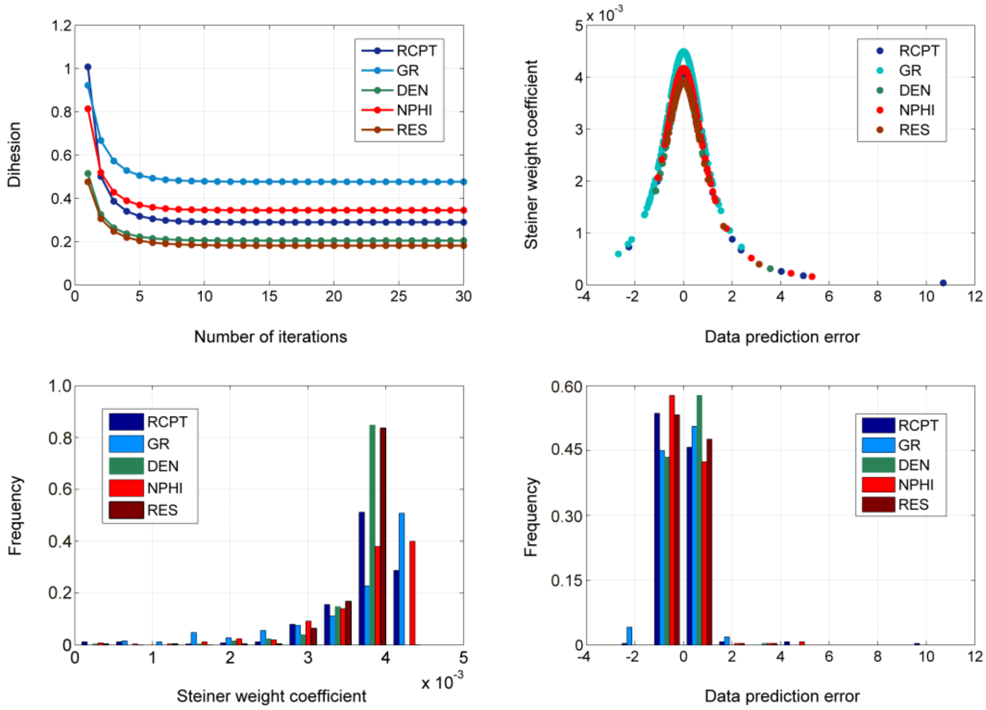

Figure 2. Weighting procedure of most frequent value based factor analysis

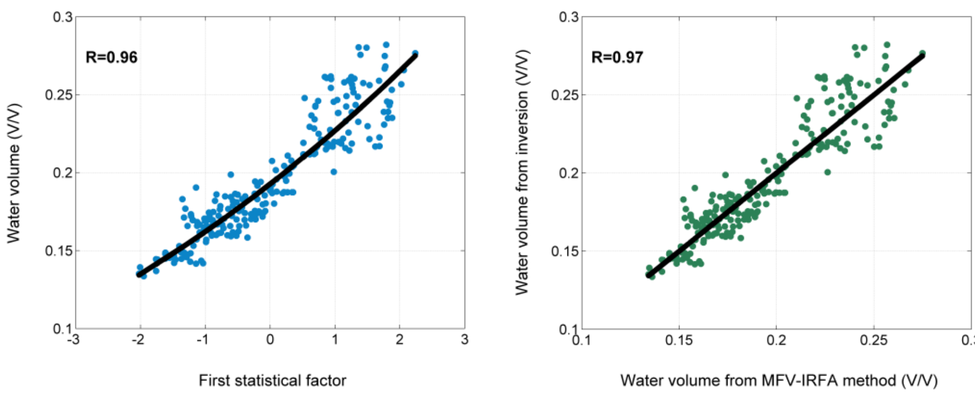

Figure 3. Regression relation between the first factor and water volume (on the left), water volume estimated by factor analysis and interval inversion (on the right)

The result of formation evaluation is plotted in **Figure 4**. In factor analysis, the cone resistance log (RCPT) could also be used, which correlated to the second factor. (In the absence of probe response equation, the inversion procedures cannot make use of this log type.) Two uncorrelated factors were calculated (F_1, F_2). The water content estimated separately by interval inversion ($V_{w,inversion}$) and factor analysis ($V_{w,MFV\text{-}IRFA}$) showed consistent results. The exponential relation between the first factor and water content was shown for three different areas in Hungary.

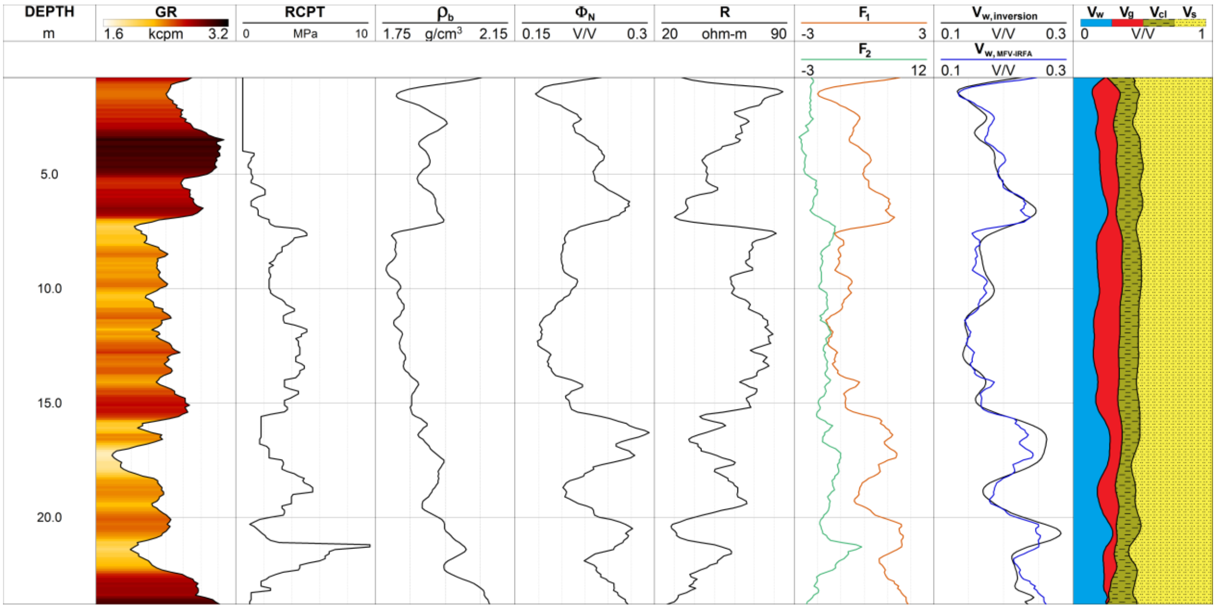

Figure 4. Water content estimation results in a Bátaapáti penetration hole

Summary of the results

In the framework of the 3 years project, new well-log-analysis methods including software implementations were developed, which were tested using both synthetic and field data sets. The practical results were confirmed in conferences and professional consultations. Beside the leading researcher, 3 MSc and 3 PhD students were employed in the project. A total of 23 full papers and conference proceedings were published in the project period. Two article were published in Q1 quality journals. The total impact factor of papers published in the 3 years project was 4.573. The paper of Szabó (2015) was awarded with the prize of Attila Meskó, which was given to the "Paper of the Year 2015" by the Hungarian Association of Geophysicists. The award was given at the annual meeting of the Hungarian Association of Geophysicists on 29 April 2016, Geological and Geophysical Institute of Hungary, Budapest.

Largely based on the results of the OTKA project, the leading researcher completed his habilitation process with the result of 98.9 % on 4 December 2015. He obtained the “dr. habil.” title from the University of Miskolc on 15 January 2016. The title of the thesis book was “Method developments for the evaluation of borehole geophysical measurements” (in Hungarian), in which 3 theses were closely related to the OTKA project. The results of the project were also utilized in the education. Two Scientific Student Research (TDK) theses and 2 MSc theses were written by the students employed in the project. Both Student Scientific Research theses were selected for the XXXII. National Scientific Student Conference (OTDK). The topic of Csilla Kalmár won the second place in the section of Earth Sciences (Kalmár, 2015b), while that of Anett Halmágyi was awarded with special prize. Since the conference presentation and extended abstract from Szabó and Balogh (2016) “received among the highest ratings from its reviewers”, editor in chief Tijmen Jan Moser invited the authors to submit a full paper to the Q1 rated journal of Geophysical Prospecting.

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Norbert Péter Szabó PhD
leading researcher