

ROMAN ŚCIGAŁA ¹***AN OPEN-SOURCE ERT DATA INVERSION TOOL FOR THE ASSESSMENT OF SINKHOLE HAZARDS RELATED TO SHALLOW UNDERGROUND WORKINGS**

Post-mining areas affected by historical shallow mining are often exposed to sinkhole hazards associated with abandoned underground workings. Reliable identification of such structures is essential for geotechnical assessment and land redevelopment. Among the available non-invasive investigation techniques, electrical resistivity tomography (ERT) is widely used for detecting shallow subsurface voids. However, interpretation of ERT measurements requires inversion processing performed using specialized software, which is frequently commercial and associated with considerable licensing costs.

This paper presents a standalone software application developed for the processing and inversion of ERT data. The software is based on the open-source pyGIMLI framework and enables ERT data analysis without requiring a dedicated Python environment or programming knowledge. The implemented workflow includes data import, quality assessment, outlier detection, inversion, and visualization of resistivity models.

The applicability of the software is demonstrated using a case study from the Upper Silesian Coal Basin (Poland), where ERT surveys were conducted to investigate shallow underground workings associated with sinkhole hazards. The obtained inversion results enabled the identification of resistivity anomalies corresponding to known underground structures. A comparison with results generated using the commercial RES2DINV package demonstrated a high degree of agreement, confirming the practical reliability of the proposed solution. The presented approach offers a cost-effective alternative for geophysical investigations conducted in mining and post-mining areas and may be useful for engineers and researchers involved in geohazard assessment and land reclamation.

Keywords: Post-mining areas; sinkhole threat; geophysical methods; ERT method; inversion software; PYGIMLI library

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1. Introduction

Shallow underground voids pose a significant threat to public safety and the environment as they may trigger the formation of sinkholes on the surface [1-3]. Many mining and post – mining areas, especially those with a long history of mining, grapple with the issue of sinkholes.

In Poland, sinkholes most often arise for anthropogenic reasons and usually are tied with mining activity [4-6]. Another example may be sinkholes inventoried in France [7], Germany [8], Italy [2] and Poland [9]. They mainly take the form of “cover-collapse” sinkholes, sometimes the form of shallow subsidence troughs above the void without a visible break in the continuity of the surface – the so-called “cover-subsidence” sinkholes – Fig. 1. In the conditions of Polish Upper Silesian Basin, shallow mining excavations (voids) located at depths of up to about 100 m [5,10] pose a significant threat to the surface in the mining and post-mining areas. Many sinkholes are formed above the old shallow headings which are going to collapse. This is confirmed by the observations presented in [6]. This is mainly because these workings were not properly liquidated by filling – in fact they are very often not liquidated at all after cancellation of the mine’s activity.

In addition, threats are posed by mining shafts driven in the 19th century and the beginning of the 20th century [11]. They pose a threat to the occurrence of sinkholes due to their improper liquidation in the past, and shafts that were illegally driven, poorly secured and not documented on mining maps.

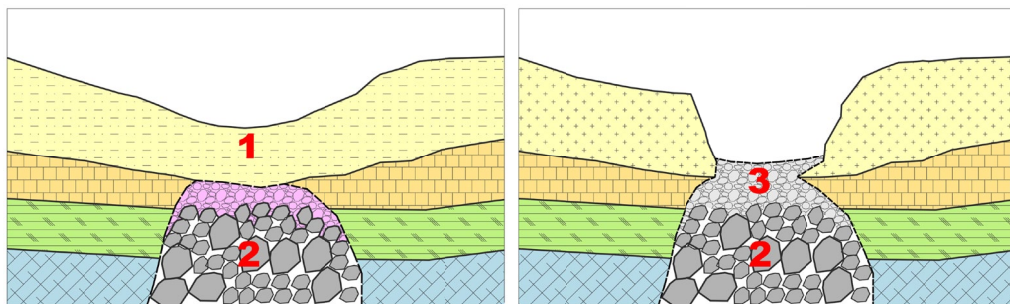


Fig. 1. Cover – subsidence (left) and cover – collapse (right) sinkholes, 1 – micro-trough created over shallow void (ground surface continuity is not broken), 2 – partially collapsed shallow void of natural (e.g. karst) or anthropogenic origin (e.g. shallow mining working), 3 – collapsed part of ground layers above the void (classical sinkhole)

In such old mining areas, the lack of historical documentation (especially mining maps) introduces additional risk, as there is insufficient information about the structure and location of shallow underground workings. In such situations, two main approaches for recognizing shallow voids exist: mining methods involving drilling or geophysical prospecting. The advantages of geophysical methods, such as relatively low cost and non-destructive procedures of application contribute to their widespread use.

One of the common geophysical methods is electrical resistivity tomography (ERT), which exploits the phenomenon of DC current flow through the layers of rock mass [12]. ERT typically employs a system of dozens of electrodes that cover the investigation area. In 2D profiling they form a straight line, while in the 3D case, they create a closed polygon, usually of rectangular

shape. The ERT method is considered one of the most effective among the commonly used geophysical methods for detecting voids in the rock mass [13]. The method can be applied in either 2D or 3D versions, which, according to some authors, provide greater depth of penetration and higher measurement resolution [14].

Advanced computational methods are used to analyse the results of measurements taken with the ERT technique, allowing for the determination of the spatial distribution of rock resistivity. This enables the assessment of resistivity anomalies that may suggest the presence of voids in the studied area. This process employs inversion method, which requires appropriate software. The most popular tool worldwide in this domain is the software package from the Malaysian company Geotomo Software: RES2DINV / RES3DINV [15]. This software uses a rectangular finite element mesh to solve the ERT data inversion problem, which imposes certain limitations on the inversion process in cases of complex rock geometry and variable terrain topography. Literature analysis indicates that a better solution is to use a triangular element mesh, as it allows for a more efficient and less geometry-sensitive description of the spatial structure of the rock mass in the inversion model. Recently, new tools for such analyses have emerged, including advanced Open-Source software libraries that provide environments for processing geophysical measurement data, upon which custom computational tools can be built. This work is dedicated to exploring this topic.

2. A short survey of recent developments in ERT data inversion software

In recent years, there has been a noticeable increase in the availability of software solutions for processing geophysical survey data. While commercial applications dominated in the past, there is now a growing development of open-source solutions, offering the significant advantage of free usage. Three main directions can be identified in the development of ERT data inversion software:

- Standalone software with a graphical user interface (GUI), such as RES2DINV/ RES3DINV [15], ERTLAB [16], ZONDRES2D [17], AGI EARTHIMAGER 2D/3D [18], RESIPY [19]
- Standalone software with a command-line driven interface for batch data processing, exemplified by BERT [20], PFLOTRAN [21,22]
- Interactive utilities, where data processing is conducted step-by-step using high-level functions designed to automate consecutive steps of the data inversion process. These utilities are built around libraries primarily written in Python or R languages. One should mention here: SIMPEG [23] and PYGIMLI [24] libraries.

The comparison of the available solutions also indicates that data-quality assessment and outlier handling constitute an important part of the ERT processing workflow. The specific implementation of these functions adopted in the INVERSE software is described in Section 4.

3. Key facts on PYGIMLI library

PYGIMLI (Python Geophysical Modelling and Inversion Library) is a comprehensive open-source Python library designed for geophysical data analysis, modelling and inversion.

It provides a flexible and extensible framework for researchers, scientists, and engineers working in the field of geophysics to efficiently process and interpret data from various geophysical methods. Key features of the library may be summarized as:

- **Multi – method support:** PYGIMLI supports a wide range of geophysical methods, including electrical resistivity tomography (ERT), induced polarization (IP), self-potential (SP), gravimetry, petrophysical modelling, seismic prospecting and more. Its modular architecture allows users to seamlessly switch between different methods and combine them for integrated geophysical investigations.
- **ERT Module:** the ERT module in PYGIMLI is particularly powerful. It provides tools for both forward modelling and inversion of ERT data. The library supports different electrode configurations, survey types, and inversion algorithms.
- **Data handling and visualization:** PYGIMLI facilitates the handling of geophysical data through its object named `DataContainer`. It is a versatile data structure that enables users to efficiently store, manipulate, and visualize geophysical survey data. The library integrates with popular plotting tool like Matplotlib for creating informative and publication-ready visualizations. Apart from built-in graphical functions, one may prepare own graphs basing on the Matplotlib library or even different graphical tools like Seaborn, Plotly Express etc.
- **Inversion framework:** PYGIMLI offers a robust inversion framework, allowing users to invert geophysical data to obtain subsurface models. The inversion algorithms are customizable, enabling researchers to tailor the inversion process to their specific needs. This flexibility is crucial for handling the inherent uncertainties in geophysical data.

PYGIMLI can be utilized in two primary ways:

- Like most Python-based code, PYGIMLI can be employed interactively, as suggested by its authors. Its optimal utilization is through the Jupyter Notebook/Jupyter Lab environment or similar platforms, although this approach requires a reliable understanding of both Python language and geophysical inversion theory.
- Standalone tools can be developed around PYGIMLI objects, streamlining the processing of geophysical survey data without necessitating programming knowledge for front-end users. The author of this paper has developed such a tool, which is presented herein.

4. The concept of the software

Presented in this paper is the software named INWISE (“INversion and VISualization for Electrical surveys”), developed by the author of this work. It operates via the Windows interface, guiding user through consecutive steps of the inversion process to achieve the final objective: the visualization of subsurface structures inspected using ERT surveys. The principal features of the application include:

- The user interface is designed and implemented using the PySimpleGui library.
- The presented here 1.0 version supports the processing of 2D ERT data obtained with Wenner α , Wenner-Schlumberger, and Dipole-Dipole arrays.
- Terrain topography can be integrated into the inversion process.
- The program accepts data in the ARES II unit format [25] as well as the UDF format [20], with imported data stored in PYGIMLI ‘s `DataContainer` object.

- All inversion-related calculations are conducted using functions of the PYGIMLI 's ERT module.
- The inversion procedure utilizes an unstructured triangular mesh generated through built-in meshing functions in PYGIMLI.
- The program facilitates pre- and post-processing of survey data to visualize and eliminate outliers.
- Results are presented using both built-in functions in PYGIMLI and primarily with native Matplotlib and Seaborn functions.

The program's workflow is structured into main menu-driven steps, each assigned a unique number, facilitating clear guidance on data preparation, inversion, and result presentation. The overall layout of the application is depicted in Fig. 2, while Fig. 3 highlights the key menu items.

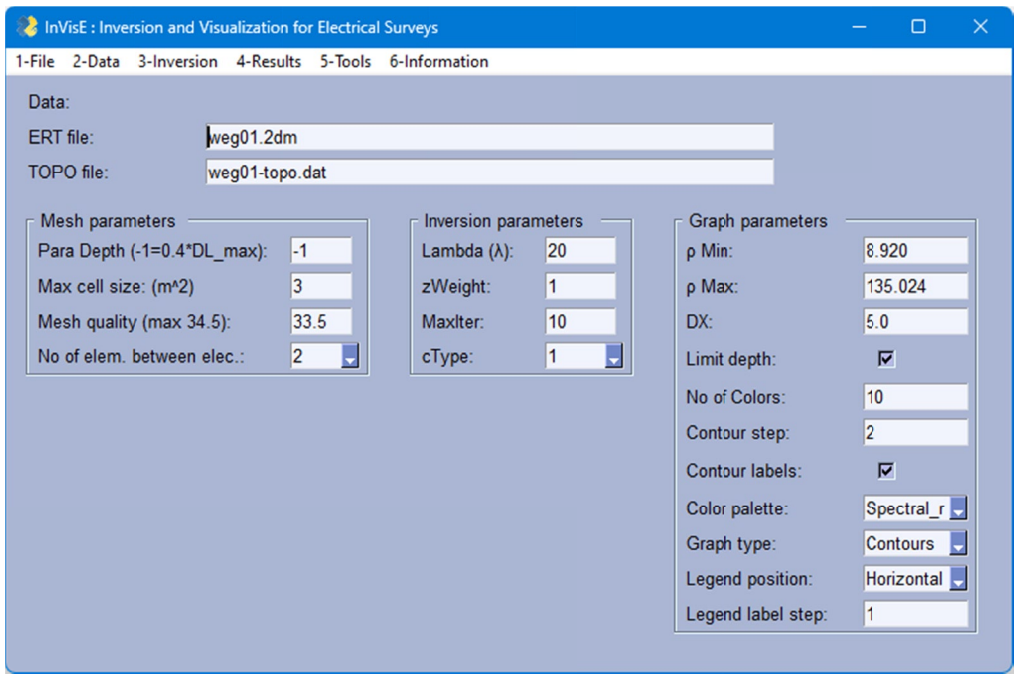


Fig. 2. General view of the application main window

1. File	2. Data	3. Inversion	4. Inversion results	5. Tools
1.1.1 - Read data from ARES file 1.1.2 - Read data from UDF file 1.2 - Read TOPO file 1.3 - Process data 1.4.1 - Save active ERT data set as ARES file 1.4.2 - Save active ERT data set as UDF file 1.5 - Quit	2.1 - Show ERT data 2.2 - ERT line profile 2.3 - Show topography effect 2.4 - Survey info 2.5 - Location of survey data points 2.6 - Normalized apparent resistivity values 2.7 - Box-Whiskers plot	3.1 - Update inversion parameters 3.2 - Show model mesh 3.3 - Inversion of ERT data 3.4 - Error graph M-D	4.1 - Show inversion results 4.2 - Show comparison (Model / Data) 4.3 - Correlation plot Data <-> Model 4.4 - Save inversion results	5.1 - Export results as (X,Y,Z) file

Fig. 3. Main menu items of the application

For simplicity, the main window integrates three thematic setup regions (Fig. 2):

- **Mesh parameters** – allow for fine-tuning of unstructured triangular mesh properties:
 - *ParaDepth* – the maximum depth for the parametric domain (in meters). If the value is -1 , the default depth is used, calculated according to the formula: $PD = 0.4 * DL_{\max}$, where $DL_{\max}$ is a maximum electrode span range used in the survey, given in meters.
 - *Max cell size* – this value used by meshing algorithm to limit the maximum area of a single triangular element, measured in square meters.
 - *Mesh quality* – This parameter constrains the shape of a single triangular element such that the internal angles of the triangle do not exceed a specified value (in degrees). The values suggested by the authors of PYGIMLI range from 30.0 to 34.0 degrees. Setting this parameter outside of this range may cause issues with system memory management and overall performance of the inversion process.
 - *Number of elements between electrodes* – this parameter allows the user to specify the number of triangular mesh elements placed between two neighbouring electrodes. Possible values are 2, 3, or 4, with the default being 2. In cases of complicated terrain topography, higher values may be used to produce a smoother mesh.
- **Inversion parameters** – includes essential parameters that influence the inversion process:
 - *Lambda* (λ) – is the regularization parameter that controls the smoothness constraints in the inversion process, thereby determining the overall smoothness of the model. In other words, it controls the regularization “strength” – higher values of *Lambda* result in a smoother model. Default value equals 5.0.
 - *zWeight* – is used to define the relative weight of strict vertical boundaries influence in the model. The default value is 1.0 (isotropic model), while values smaller than 1.0 introduce a layering effect to the model, with the side effect of decreased smoothness.
 - *MaxIter* – define maximum number of iterations during inversion process. Default value is 10.
 - *cType* (“constraint-type”) – the default value is “1”, which applies first-order smoothness in the inversion process. A value of “2” applies second-order smoothness, minimizing the curvature of the model. Zeroth-order smoothness can be used with a value of “0”, where only the norm of the model difference to the reference model is minimized. Additionally, one can “join” the above algorithms by using the values: “10” and “20”.
- **Graph parameters** – comprises settings for graph presentation:
 - $\rho_{\min}$, $\rho_{\max}$ – these settings allow the determination of the range of resistivity values displayed on the graph.
 - *DX* – the grid step size over X-axis (along the line path).
 - *Limit depth* – allows for displaying only the portion of the inversion mesh up to the depth of penetration resulting from the maximum span of the electrodes for a given electrode array.
 - *No of colours, contour step, contour labels, colour palette, legend position, legend label step* – these parameters allow for fine-tuning the appearance of the graph.
 - *Graph type* – gives two options for presentation of resistivity distribution:
 - as a map of resistivity distribution represented by averaged values for each triangular mesh element (Fig. 12),
 - as an interpolated contour map (Fig. 13).

On both maps values over ρ_{Max} and under ρ_{Min} are marked with fixed colours: purple and grey respectively. The black dashed lines indicate the estimated measurement depth based on the electrode spacing and the selected measurement array.

More detailed explanations of the above-mentioned parameters related to mesh creation and the inversion procedure can be found, for example, in the documentation [26].

The key steps of the computational procedure performed using the INVERSE program are as follows:

1. Data reading.
2. Pre-processing: analysis of data quality, removal of outlier data points, mesh generation, configuration of inversion parameters.
3. Inversion procedure.
4. Post-processing: generation of resistivity distribution maps, assessment of model accuracy compared to survey data.

Due to the limited scope of this article and considering that the computational procedures in various software programs for geophysical data inversion are quite similar, these procedures will not be presented here. Instead, we will dedicate a few words to the program's capabilities in analysing ERT measurement data, particularly focusing on the identification and elimination of outliers.

One of the specific features of the INVERSE software is the integrated quality-control procedure for identifying and removing potential outliers from ERT data. In the current version of the program, three complementary outlier-handling procedures are available:

- During the pre-processing stage (before performing the inversion):
 - Manual, visual identification of outlier data points. This is done using a plot of the measured apparent resistivity values at different pseudosection levels, as shown in Fig. 9. The user can select outlier points with the mouse. This procedure is accessible from the “2.6 – Normalized apparent resistivity values” menu function. Similar procedure is available in the RES2Dinv software [15].
 - Automatic identification of potential outliers using a box-and-whisker plot. The procedure is based on the interquartile range (IQR) and is performed separately for each pseudosection level (Fig. 10). Measurements falling outside the IQR-based whisker range are identified as potential outliers and can subsequently be removed from the dataset. This provides a simple statistical criterion for data-quality assessment prior to inversion.
- After performing the inversion:
 - In this case, the deviation between the measured apparent resistivity values and those calculated from the inversion model is analysed. The deviation is expressed as a percentage error, and a histogram is generated to show the frequency distribution of the errors (Fig. 11). A vertical line indicates the user-defined rejection threshold, which can be interactively adjusted using a slider. The threshold is not predefined and can be selected according to the quality of the dataset and the desired level of data filtering. Measurements exceeding the selected threshold are marked for rejection and can subsequently be removed from the dataset. The inversion can then be repeated using the filtered dataset. A similar user-controlled error-based filtering approach is available in RES2DINV software.

5. An example of using INVISE software to assess hazards of shallow underground structures potentially leading to surface deformations

The ERT survey was conducted in the post-mining area of currently inactive “Szttygarka” Training Mine – Museum located in the city of Dąbrowa Górnicza [27], which is located in the Upper Silesian Coal Basin, Poland – Fig. 4.



Fig. 4. Geographical location of the Upper Silesian Basin

The shallow underground workings are situated beneath a small park surrounded by urban buildings – Fig. 5a. The accessible underground workings extend for approximately 800 meters. Since January 2010, the mine has been open to the public, featuring an underground tourist route that spans 650 meters with a vertical difference of 25 meters. Access to the mine is provided



Fig. 5. The survey site view (a) and the ARES II unit used for measurements (b)



In the past, small cover-subsidence sinkholes appeared on the surface above the underground workings, with depth of 0.2-0.3 m. The main cause of their formation, apart from the shallow location of the workings, was the infiltration of surface water into the workings, which induced suffusion transport of loose overburden rocks into the mining workings. The terrain was subsequently restored by filling in the sinkholes.

To assess the current state of the near-surface rock layers above the workings, investigations were conducted using the ERT method. The placement of the ERT profile line was constrained by the layout of the underground workings and the existing land configuration and development. The optimal profile location on the surface, which was ultimately used, is shown in Fig. 6. The profile line comprised 48 electrodes spaced 1.5 meters apart, resulting in a total profile length of 70.5 meters. The profile's position relative to the underground workings is illustrated in Fig. 6. The investigation was conducted along this profile line using a Dipole-Dipole array.

The measurements were conducted using ARES II equipment [25], and the results were processed using the INVERSE software. The apparent resistivity pseudosection is presented in Fig. 8. In the first step, a quality analysis of the measurement results was conducted to eliminate outlier measurements. For this purpose, the appropriate functions of the INVERSE program: “2.6-Normalized apparent resistivity values” and “2.7-Box-whiskers plot”, were used. The corresponding visualizations are shown in Figs. 9 and 10. In both figures, an obvious outlier measurement is indicated with a red ellipse, which was eliminated before the inversion. Additionally, an error analysis was performed during the post-processing stage, and measurement points where the error between the model and the measurement exceeded 10% were eliminated. Fig. 11 shows the settings of function “3.4-Error graph M-D”, that implements this data filtering. The inversion results are presented in the next section of the paper. Meshing of the model and inversion was conducted with the following values of key parameters: $\lambda = 100$, $zWeight = 0.2$, $Max\ cell\ size = 1\ m^2$.

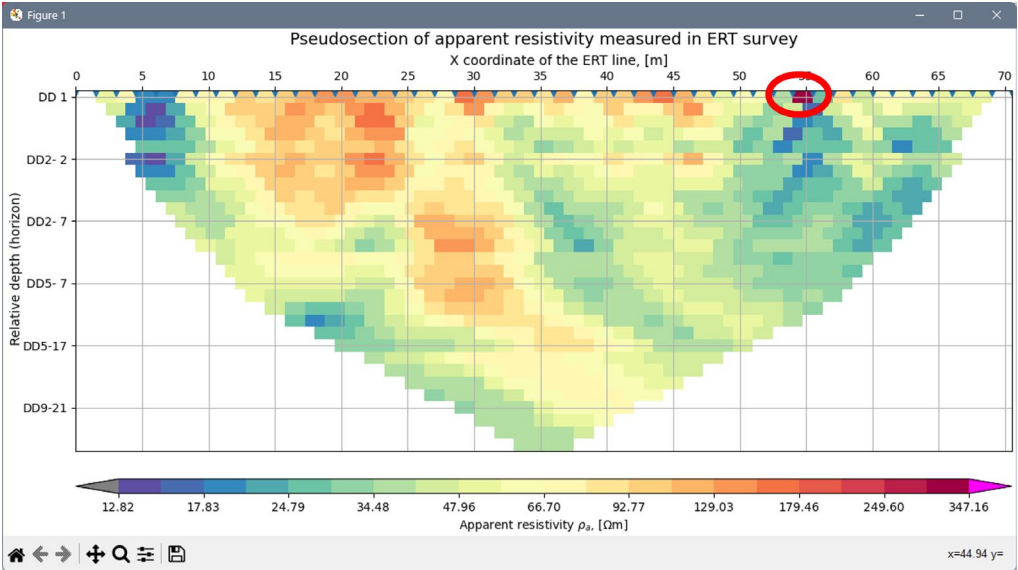


Fig. 8. Pseudosection plot with marked exemplary outlier. Graph created using “2.1-Show ERT data” function

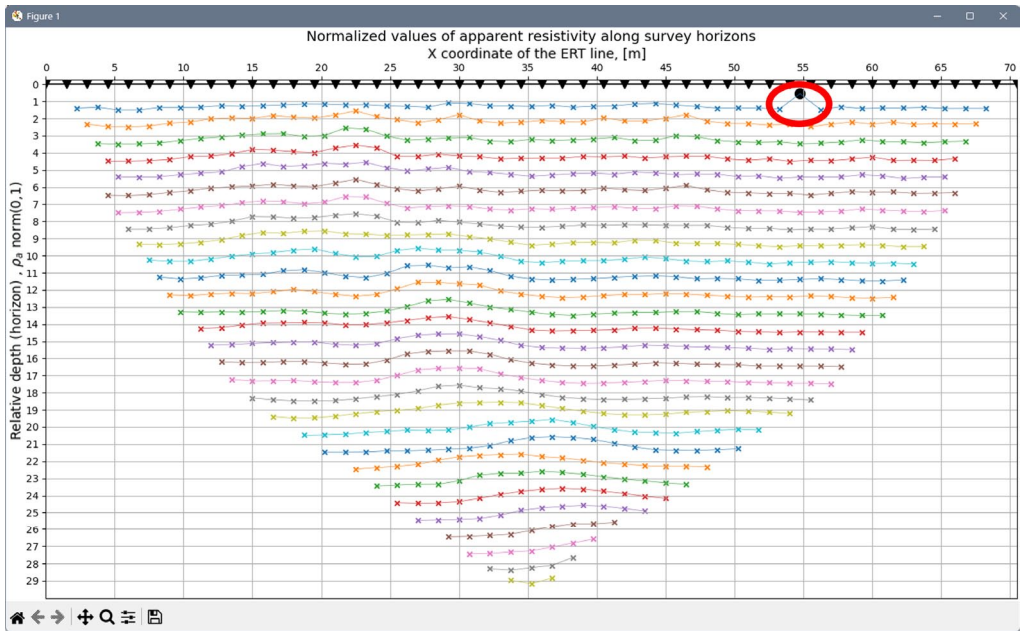


Fig. 9. Line plot of measured apparent resistivity values with marked exemplary outlier.
Graph created using “2.6-Normalized apparent resistivity values” function

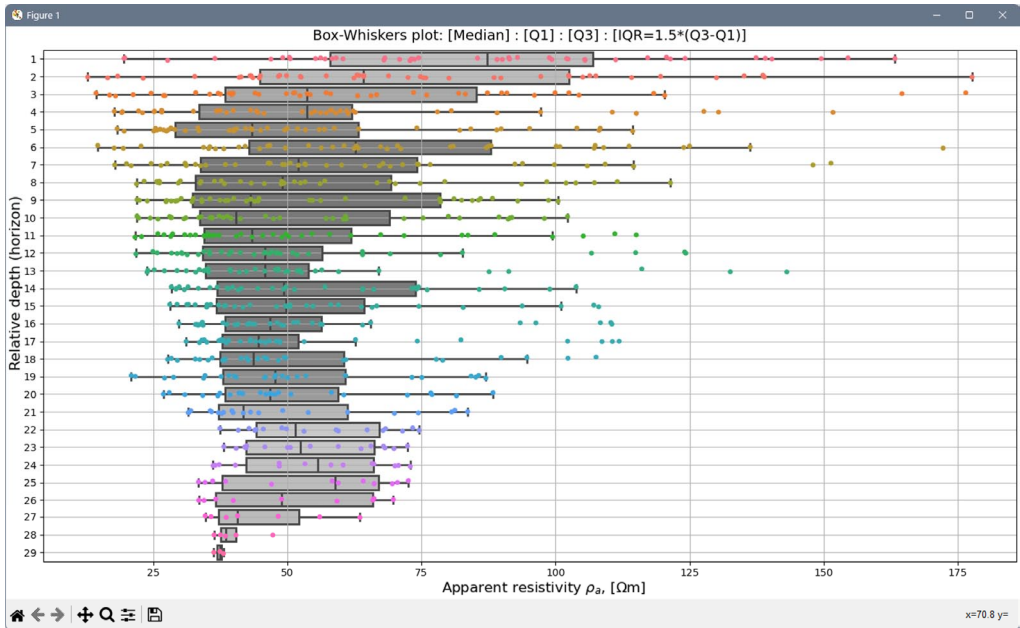


Fig. 10. Determination of outliers with box-whiskers graph - outliers located outside whiskers.
Graph created using “2.7-Box-whiskers plot” function

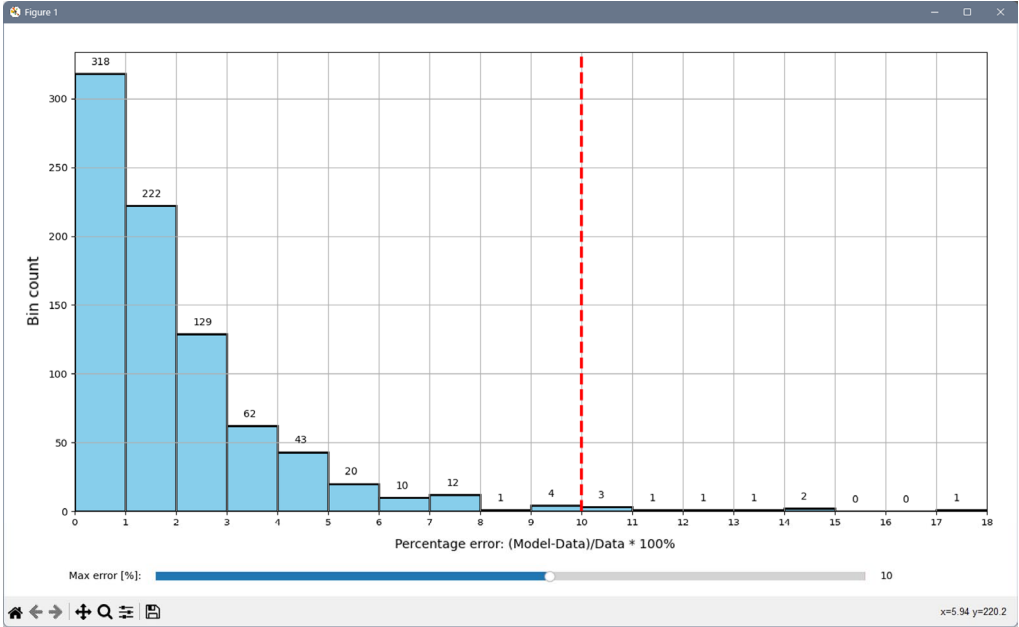


Fig. 11. Determination of outliers based on the histogram of deviation between ERT survey data and modelled apparent resistivity (exemplary outliers located to the right of red dashed line).
Graph created using “3.4-Error graph M-D” function

6. Discussion of results

The inversion results are presented in Figs. 12 and 13. Fig. 12 shows the resistivity distribution determined as the average value for each mesh element, while Fig. 13 displays the interpolated resistivity distribution in the form of a contour map. Both figures were generated using the “4.1-Show inversion results” function. The inversion quality measures are presented on the graph in the upper-right corner. Values obtained in the considered case are: $RRMS = 2.82\%$, $\chi^2 = 0.90$. These quantities are the misfit measures and should be understood as:

$$RRMS = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{d_i - f_i(m)}{d_i} \right)^2} \quad (1)$$

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N \left(\frac{d_i - f_i(m)}{e_i} \right)^2 \quad (2)$$

Where:

- N – number of data points,
- d – data vector of N points,
- m – model vector,
- $f(m)$ – forward response of the model m .

Additionally, the program allows for generating a graphical assessment of inversion quality by comparing the pseudosection obtained from the measurement with that generated in the final step of the inversion procedure. This comparison is presented in Fig. 14, with the upper section showing the measurement and the middle section showing the model. The lower section displays the ratio of these values for each cell in the pseudosection – where a value of “1.0” (white colour) indicates perfect agreement between the measurement and the model, values below “1.0” (blue colour) indicate underestimated apparent resistivity in the model, and values above “1.0” (red colour) indicate overestimated apparent resistivity. This graph is generated by the “4.2-Show comparison (Model/Data)” function.

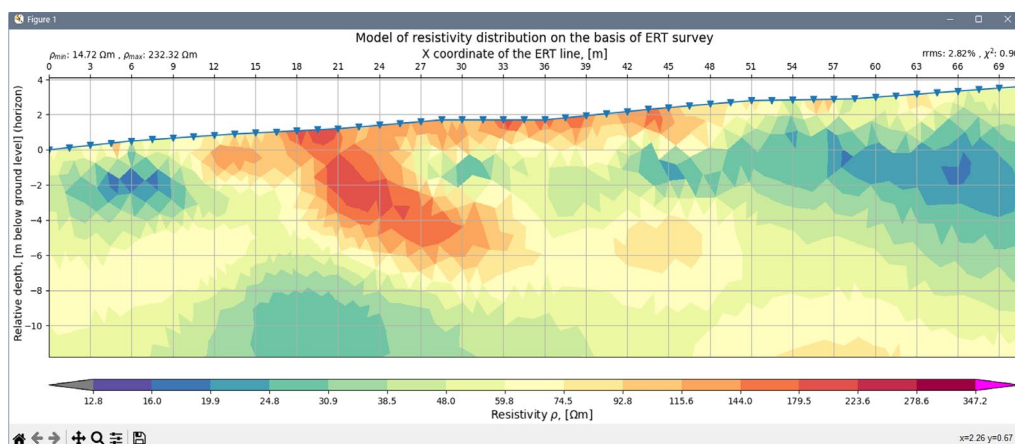


Fig. 12. The distribution of resistivity in the near-surface rock layers in the region of the mining workings presented using the averaged values for individual mesh elements. Graph created using “4.1-Show inversion results” function

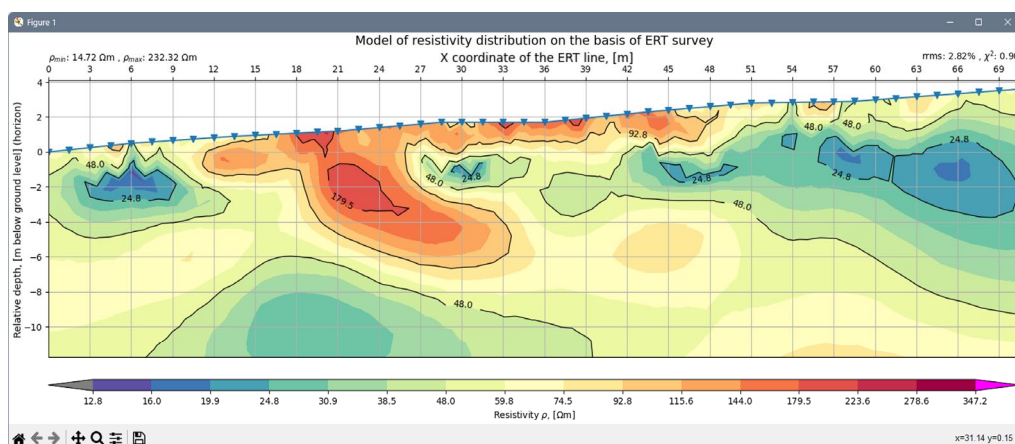


Fig. 13. The distribution of resistivity in the near-surface rock layers in the region of the mining workings presented using interpolated contours. Graph created using “4.1-Show inversion results” function

Analysing the obtained interpretation of the measurement results presented in Figs. 12-13, the following can be stated:

- Due to the length of the ERT profile line being equal to 70.5 m, the estimated depth of penetration was about 11-12 m. Therefore, the obtained distributions practically concern a fragment of the rock mass from the ground surface to the roof of the underground workings of the Level 1 of the mine.
- In carried out measurements, there are visible two significant anomalies in the resistivity distribution (Figs. 12-13):
 - Anomaly No. 1 – between the 18th and 27th meter of the ERT line, where survey line crosses the “West drift Level 1” of the mine. This is high resistivity anomaly.
 - Anomaly No. 2 – between the 57th and 67.5th meter of the ERT line, around “South drift Level 1” and the workings of Level 3 – “Inclined drift 2 south”. This is low resistivity anomaly.
- The location of anomaly No. 1 coincides with the workings of the shallowest Level 1 of the mine. The extensive area of the high-resistivity anomaly No. 1 suggests the possible existence of rock loosening between the workings and the ground surface. This is also the site of a previously formed sinkhole, indicating a potential hazard for secondary sinkhole

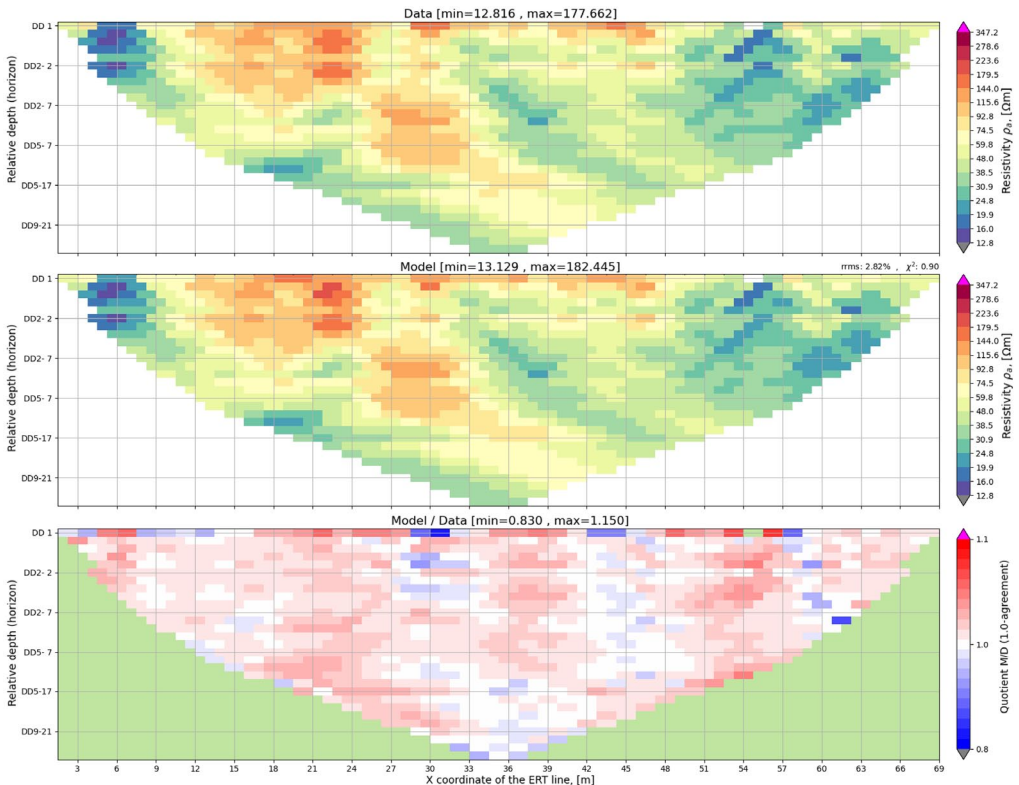


Fig. 14. The comparison of the pseudosection obtained from the measurement with the one generated in the final step of the inversion procedure. Graph created using “4.2-Show comparison (Model / Data)” function

formation in the future. The interpretation of low-resistivity anomaly No. 2 is difficult to assess due to its position at the end of the line, where there is a lack of reliable data for the inversion process, so in this case any further conclusions should be rejected.

- The in-situ inspection of the Training Mine underground workings in the zone of anomaly No. 1 revealed periodic infiltration of surface water from precipitation. This indicates the possibility of mechanical scouring, which may intensify the sinkhole hazard due to the leaching of loose rock material into the underground workings. Fig. 15 shows an example of local water seepage infiltrating from the surface into the workings. Several such locations were identified during the inspection.

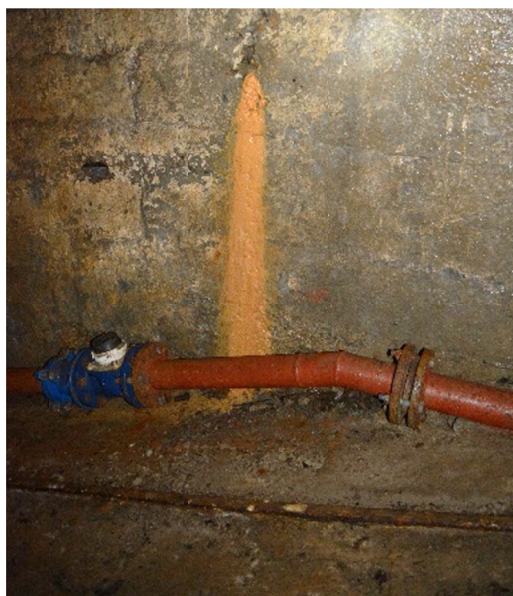


Fig. 15. An example of local water seepage infiltrating from the surface into the underground working

7. Evaluation of inversion results against RES2DINV software

To evaluate the quality and reliability of the inversion results obtained using the INWISE software, the RES2DINV program was employed for comparison. The same ERT dataset and electrode configuration were processed using RES2DINV. The RES2DINV inversion included topography modelling using the damped finite-element method with average topographic trend removal. The inversion was performed using seven iterations, Gauss–Newton Jacobian calculation, robust data and model constraints, an extended model, and trapezoidal finite elements. The topography distortion damping factor was set to 0.75. The resistivity distribution obtained with RES2DINV is presented in Fig. 16, employing the same colour mapping as in Figs. 12–13. A comparison of the results obtained with INWISE (Figs. 12–13) and the commercial RES2DINV (Fig. 16) shows a high degree of agreement in the resulting resistivity distributions. TABLE 1 provides a quantitative comparison of key quality metrics: mean absolute error (MAE), mean

squared error (MSE), root mean squared error (RMSE), and R-squared (R^2), calculated with respect to the measurement results. As shown in the table, the values of these metrics are closely aligned, further confirming the similarity in performance between the two software tools. Additionally, Fig. 17 presents histograms of absolute errors, while Fig. 18 shows correlation plots between measured and modelled apparent resistivities for both solutions. These figures also demonstrate the comparable quality of both approaches.

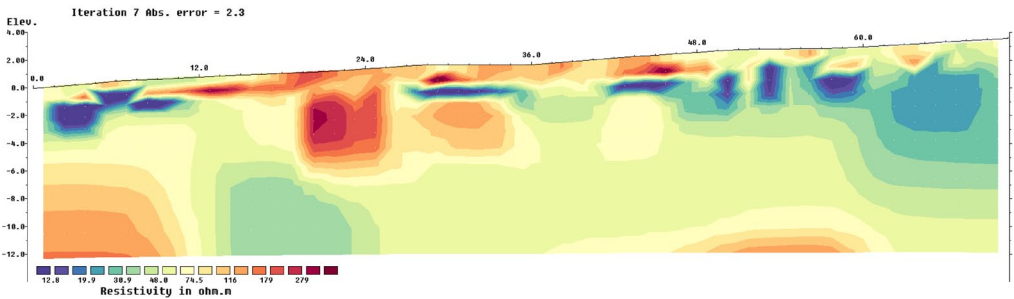


Fig. 16. The distribution of resistivity obtained with the RES2DINVsoftware

TABLE 1

Error measures: modelled vs measured apparent resistivity

Software:	Error measure:	MAE	MSE	RMSE	R^2
		$[\Omega\text{m}]$	$[\Omega\text{m}]^2$	$[\Omega\text{m}]$	
	INVISE	1.147	4.685	2.165	0.994
	RES2DINV	1.261	9.482	3.079	0.989

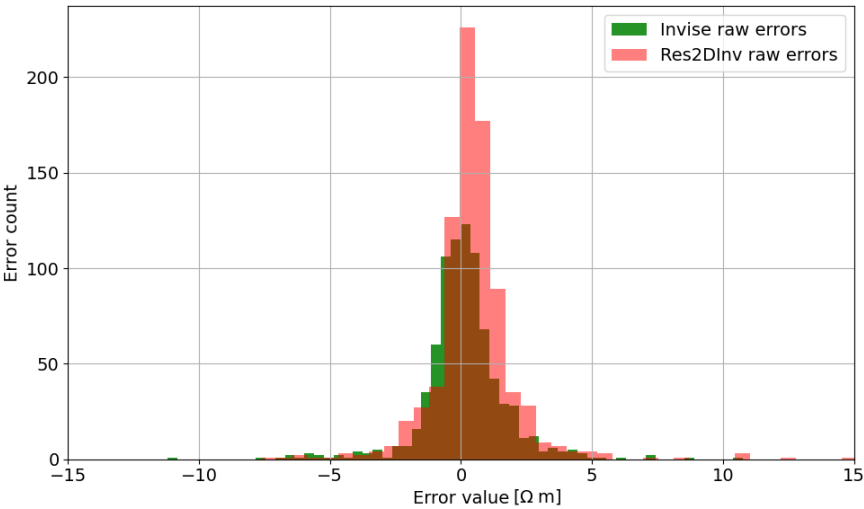


Fig. 17. The histogram of apparent resistivity raw (signed) errors

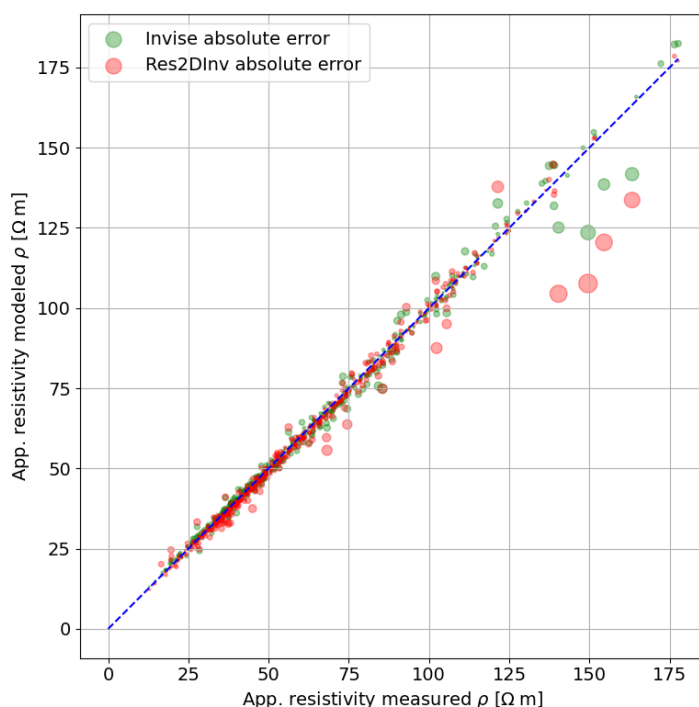


Fig. 18. The correlation graph of modelled vs measured apparent resistivity

8. Conclusions

With reference to the developed software, the following conclusions can be drawn:

1. Geophysical surveys in investment areas located in regions of anticipated sinkhole hazard are a good complement to geotechnical recognition of the properties of near-surface rock layers in a non-invasive manner. Particularly useful is the ERT method, where relatively low effort and resources can provide insight into the existence of shallow voids in the rock mass.
2. The developed software directly interfaces with the results of the ERT measurements conducted using the ARES II equipment, without need for any additional data conversion. It is possible also to load the data saved in the UDF format as the standard of the PYGIMLI library.
3. Current version of the INVISE software described in this paper incorporates essential functionalities required for 2D analyses of the ERT surveys. There are further plans to continue development efforts on the application, primarily focusing on improving the analysis of measurement data quality, expanding computational capabilities and extending import of data with different formats.
4. The presented case example confirms practical usability of PYGIMLI library, which may be incorporated into own software solutions with added different functionalities extending the processing of ERT survey data capabilities given by PYGIMLI.

5. The quality of the resistivity distribution obtained using the INWISE software is comparable to that achieved with the commercial RES2DINV package, as demonstrated by the similarity of the inversion models and the quantitative error measures presented in this study.
6. The comparison with the commercial RES2DINV software demonstrated that the developed INWISE application provides inversion results of comparable practical value while eliminating the need for expensive software licenses. Owing to its open-source foundation, standalone architecture, and possibility for further customization, the software may constitute an attractive alternative for engineering institutions, universities, and practitioners involved in post-mining land assessment and sinkhole hazard investigations.

The results presented in this study indicate that modern open-source geophysical frameworks can successfully serve as a basis for the development of practical engineering software dedicated to ERT data interpretation. The proposed INWISE application demonstrates that reliable inversion of ERT data can be achieved without the use of expensive commercial software, which may facilitate broader adoption of geophysical methods in post-mining land assessment and sinkhole hazard investigations.

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