




## Methods of introducing a discontinuity line into a numerical model of a hard coal deposit

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**Keywords:** geology, mining, numerical model of mineral deposit, mining numerical maps, discontinuity lines, faults, AutoCAD Civil 3D

**JEL Classification:** C63, L71

### Abstract

The largest problem that we encounter when creating a numerical model of a hard coal deposit is to insert discontinuity lines representing faults, seams junction lines, wedging, etc. The faults introduced on the map of the seam are mostly flat polylines, while we do not know the altitude ordinate. In order to determine the spatial position of the faults, authoring methods have been developed and implemented in the Geolisp software and in the CAD system. This article presents the method based on calculating the spatial position of the fault with respect to the existing contours, which arrive at it from both sides, the method based on the assumption that the inclination of the seam in front of and behind the fault is constant, the procedure involving the performing of independent surfaces of the upthrow and downthrow side with extrapolation by the Kriging method, and the procedure requiring the transfer of the fault from the above-lying seam or a Carboniferous roof. The solutions given in the article are successfully used in most mines in Poland. The correct introduction of the fault course is important for the accuracy of forecasting the impact of the mining operations on the rock mass and the surface area.

### Introduction

In most Polish hard coal mines, the information system on mining space is currently in use, which contains information necessary for its safe operation, including geological and mining data, the structure and quality of the deposit, workings network, ventilation, mining hazards, the impact of mining operations on a rock mass and surface area, etc. This system enables the preparation of maps, reports, and other documentation; it also allows for the search, view, and download of data. The system enables the creation of a numerical deposit model, facilitates mining plant operations and the design of

new operations and increases the accuracy of forecasts of the impact of exploitation on the surface (Sokoła-Szewiola & Poniewiera, 2019).

The software used in the mining industry worldwide is presented in the paper (Krawczyk, 2019). Currently, the Geolisp elaborated by Marian Poniewiera is the most popular software used to create and manage digital mining maps in Poland. It operates in a CAD (computer aided design) software platform, such as AutoCAD, BricsCAD etc. and allows an automation of the most common operations in the field of mining map creation and shares them for management in the entire mining company (Geolisp, 2022).

The largest problem that we encounter when creating a numerical model of the deposit is the insertion of the faults. The faults drawn on the seam maps are flat polylines; their elevation is unknown. To determine the spatial position of the faults, proprietary methods are implemented in the Geolisp software, in the CAD system have been developed. This article presents methods based on: calculating the spatial position of the fault using existing contours that reach it from both sides; the assumption that the inclination of the seam in front of and behind the fault is constant; the implementation of the independent surface of the upthrow and downthrow side with the Kriging extrapolation function, a procedure involving the transfer of a fault from a higher lying seam or the Carboniferous strata and the method of closed areas. The presented methods can be used both when providing a deposit using a solid method, and when using a triangles grid. The Geolisp software allows the insertion of faults in accordance with the mentioned algorithms.

Of course, solutions to the problem of introducing discontinuity lines in other software are known, e.g., MineScape and DataMine (DataMine software, 2022), Surfer (Golden software, 2022), Petrel (Slb, 2022), RockWorks (Rockware, 2022), Move Midland Valley (Petex, 2022), Georeka (Georeka, 2022), Minex and Surpac (3DS, 2022), Vulcan (Maptek, 2022), and others. Hence, there are a large number of publications on examples of fault modeling using the mentioned software, as well as containing proposals for new solutions to achieve high model accuracy. Important works in this field include (Wu & Xu, 2003; Wu, Xu & Zou, 2005; Zhu et al., 2006; Jelonek, Poniewiera & Gąsior, 2015; Jiskani & Siddiqui, 2019; Jia, Li & Che, 2020).

This article attempts to organize the existing solutions, as well as present new experimental methods that determine the course of faults in the space with limited data and where there are many faults in the deposit. It should be noted that the correct insertion of the fault course is important for safe mining operations, in particular in conditions of mining hazards occurrence, including induced seismicity, and for the accuracy of forecasting the impact of mining operations on the rock mass and surface.

## Research methodology

### Inserting the faults into the deposit model

The examples given in this paper originates from the mines of the Upper Silesian Coal Basin located in the south of Poland. The analyzed deposits belong to Polska Grupa Górnicza S.A. and Jastrzębska Spółka Węglowa S.A. These companies use: Geolisp, MineScape, and Surfer software for geological modeling.

The work sequence for a model generation is as follow.

- Data collection: boreholes, elevation datapoints, and faults.
- Generating a numerical model of the deposit.
- Insertion of faults and other discontinuity lines.
- Verification of the created deposit model.

#### 1. Numerical model of the deposit

The numerical model of the deposit is, in fact, a set of TIN surfaces – a network of triangles whose vertices are points with specific  $X$ ,  $Y$ , and  $Z$  coordinates. The  $X$  and  $Y$  coordinates of the surface points

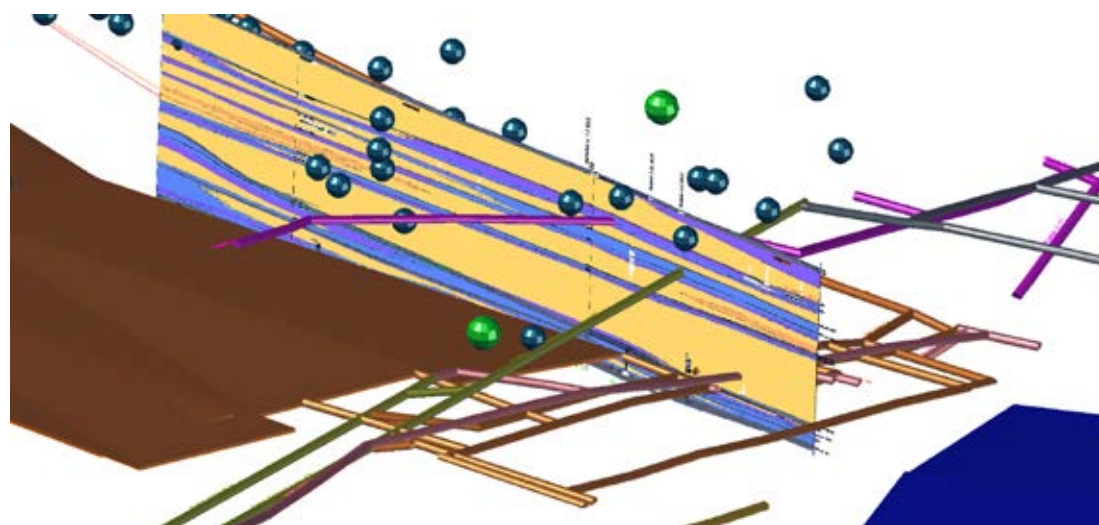


Figure 1. Deposit model containing a geological cross-section, development workings, tremor focal points, and exploitation plots

overlay with the insertion point of the object, while their  $Z$  value equates to the value of the selected attribute (elevation datapoint, sulphation, thickness, etc.).

New points on the surface can be created based on data from drawings (e.g., elevation points of chemical composition data blocks), thickness (e.g., only unmined mineral or only mined interlayers, etc.), external text files in various formats, and database records, e.g., Oracle Spatial. The surface can be visualized by means of a spatial grid, an isoline, a hypsometric map, etc. We can display the seam floor surface along with the existing and designed workings, tremors, (Kowalczyk, Hadam & Poniewiera, 2019) etc. (Figure 1).

The second – solid – method of presenting the deposit is to generate a dense grid of cuboids mapping the entire rock mass. Based on the triangle grids, a solid model can be generated and vice versa from a solid model the surface of any seam can be obtained. The correct introduction of the fault course is important, e.g., for the accuracy of forecasting the impact of mining operations on the rock mass and the surface area (Poniewiera, 2018).

## 2. Preparation of input data

First of all, we create a database of geological boreholes, elevation datapoints, chemical analyzes, etc. The proper data assignment to the seam is crucial for the construction of the deposit model. This is usually the most time-consuming element in creating a model. If the borehole does not cross all seams, then the missing data must be interpolated.

On each map – numerical or paper – there is a trace of the intersection of the fault with the given seam. In practice, it is a flat polyline and we do not know its elevation altitude. Usually the fault throw is known, although this is not always reliable information. Often the throw and inclination are correctly defined only after the second iteration of the model creation, when we have all the seams developed.

When developing faults on the map, we should pay attention to the following elements (Figure 2):

- All faults should be drawn with a double line (top and bottom). Discussed programs automatically generate the second line based on the throw and inclination, but it needs to be verified.
- Locations where the fault changes its inclinations must be marked and described (insertion of an appropriate block). If the fault fades in the seam – at its last point, a throw value of zero must be entered.

- The fault polylines should not contain arcs or too many vertices. Before starting work, it is worth conducting the simplification of all lines.
- Topology verification. Namely, at intersections, the polyline should be cut and there should be no breaks in the fault line. Each fault should end on a contour line, on another fault line, or throw point equal to zero.

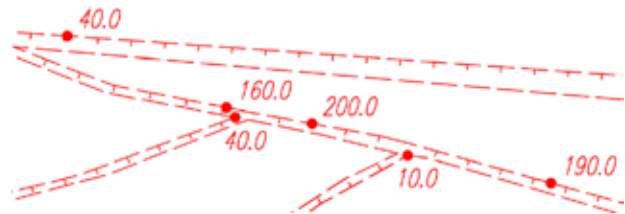


Figure 2. Preparation of the fault line on a numerical map. Complex line represents the footwall, dashed line is the upthrow, and text is the throw of the fault

To create the deposit model, other data such as floor contours or fold axis are not really required, but they help to obtain exactly the result we want to find. Similar to faults, other lines should be drawn with possibly straight lines with the minimum number of vertices.

Most often we use such data since:

- The seam floor contour lines, if available, must have a defined elevation. There should be quite a few contour lines, especially at the locations of faults crossings.
- It is a good idea to make a contour line of the area in the form of a closed polyline, and all other lines should be extended up to this contour line. This facilitates the finding of the wrong contours if we know that each open contour must end at a fault or at a boundary line. The top of the contour should not be inside the fault zone; if it happens, it should be relocated.
- Elevation data points assigns the  $Z$  value to the fault line in a specific location, i.e., in exploratory workings. It is recommended to insert such points at the faults intersection and at the faults ends.
- Other discontinuity lines, such as the fold axis, on a numeric map can be saved in the form of a flat or spatial polyline. It is required to pay attention to the intersection of the fold axis with contour lines, both lines must bend at the same place and have the same elevation assigned.

## 3. Inserting the fault with a steady slope method

The method assumes that the inclination of the seam is the same on both sides of the fault. The

disadvantage of this procedure is that the fault throw needs to be known. The algorithm of the steady slope method involves:

- Creation of the triangles grid based on measurement data, e.g., from geological holes.
- Finding all intersections of the side of the triangle with faults (Figure 3a). In the case of a large number of small faults that do not intersect with any triangle, we act iteratively: first, we introduce faults with the largest throw, which compacts the grid, then we introduce smaller faults.
- Calculation of a  $h_i$  – as the fault throw – in the intersection point (if the fault throw is not constant, we calculate it as the weighted average from the nearest measurement points), see Figure 3b.
- Calculation of the elevation of the fault –  $H_i$  using formula (1).
- Inserting discontinuity lines on the surface of triangles.
- Extending and smoothing the surface of the triangles to the border of the entire area.
- Deletion of triangles located inside the fault (Figure 3c).

Calculation of the elevation of the fault  $i$ ,  $H_i$ , uses the expression:

$$H_i = H_B - \Delta h_i - \sum_{j=1}^{i-1} h_j, \quad i = 1 \dots m \quad (1)$$

where

$$\Delta h_i = D_i \cdot \frac{H_B - H_{A'}}{D_{AB}} \quad (2)$$

and  $H_{A'}$  is calculated from:

$$H_{A'} = H_A + \sum_{i=1}^m h_i \quad (3)$$

Here,  $h_i$  represents the throw of the  $i^{\text{th}}$  fault that crosses the side of the triangle,  $m$  denotes the number of faults,  $H_A$  is the elevation of the seam floor in the borehole A,  $H_B$  is the elevation of the seam floor in the borehole B,  $H_{A'}$  is the elevation of the seam floor, as it would be in the borehole A, if there was no fault,  $D_{AB}$  is the horizontal distance between boreholes A and B,  $D_i$  is the horizontal distance between borehole B and the fault  $i$ ,  $\Delta h_i$  is the difference between elevation of the seam floor in borehole B and the line of the fault  $i$ , as would occur if there was no fault, and  $H_i$  is the elevation of the upper surface of the fault  $i$ .

#### 4. Existing contours method

The existing contours method involves calculation of the spatial location of the fault based on existing contours of the seam floor, which reaches the fault from both sides (Figure 4). Usually, mining

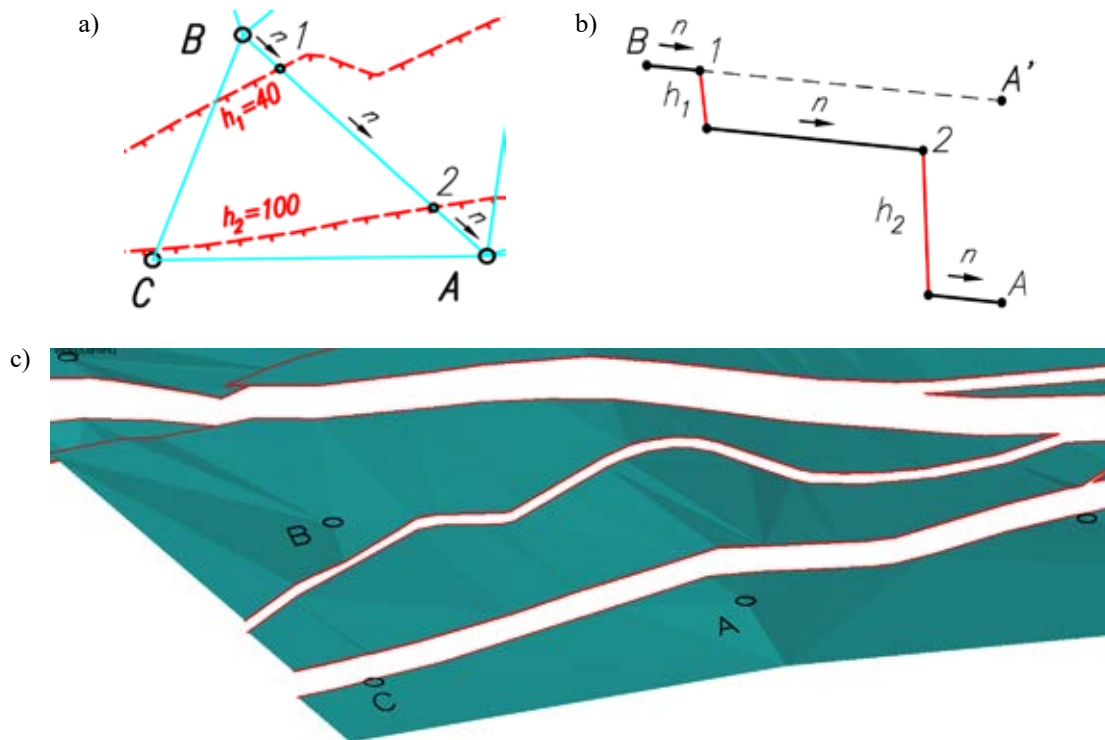


Figure 3. Inserting the faults using the steady slope method: a) top view, b) side view, and c) isometric view. Here,  $n$  is the inclination of the deposit, constant throughout the entire AB section, and  $h$  is the throw of the fault

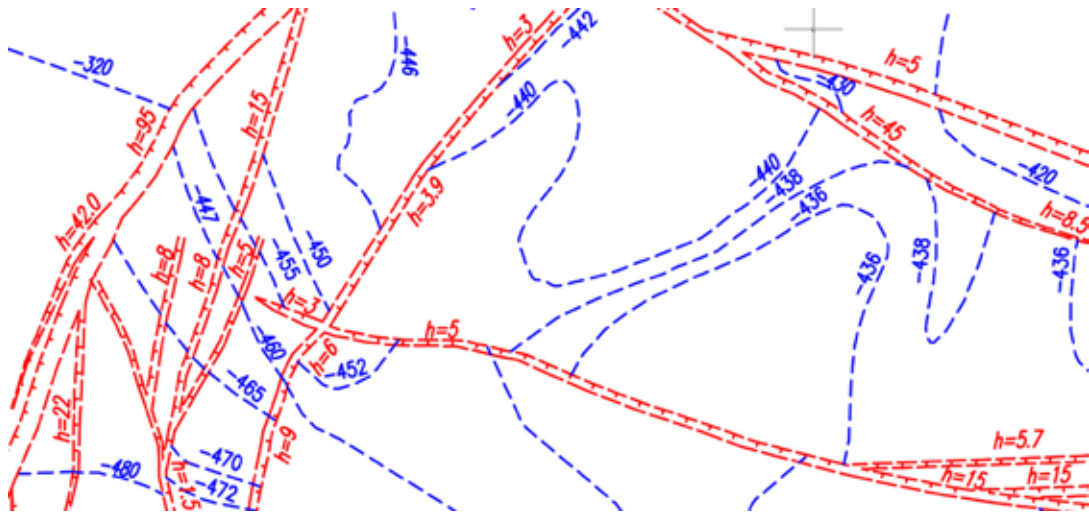


Figure 4. Inserting of a fault based on the existing contours method

maps with floor seam contours can be digitalized and contours can be concentrated, so that at least two isolines reach every fault. Such procedure allows for a quick preparation of the deposit model, but there is a risk of duplication of errors from paper documentation. In practice, other methods mentioned in the article should be used at first, in order to create a deposit model containing faults. Based on the created model (first iteration), the contour lines need to be generated and then the contour lines should be corrected manually. The advantage of this method is to obtain the exact result we want to receive. In this way, it is easy to implement folds or other geological disturbances. An important advantage is that this method does not require knowledge of the fault throw.

Algorithm of the existing contours method requires:

- Concentration of the isolines, so that every fault can be determined. Figure 4 shows the original situation before isolines concentration.
- Finding all intersections of isolines with faults.
- Inserting of auxiliary points at the points of fault intersections.
- Assigning the elevation to the faults and contours at the intersection with the isolines and other objects (fold axis and auxiliary point).
- Creation of a deposit model based on geological boreholes, faults, contours, folds, and points (the sequence of objects inserting into the model is important, faults must be entered from the largest to the smallest).
- Deletion of triangles located inside the fault.
- Checking of the fault throws, distances to adjacent seams, inclination of each triangle, etc.
- Generating new isolines of the seam floor, correcting and repeating the above activities,

if necessary, until the deposit model meets expectations.

#### 5. Separate surfaces method

The most accurate way, requiring a relatively large amount of data, is to prepare separate seam floor surfaces on both sides of the fault. Then, using geostatistical methods (Kriging), extend these surfaces and find the elevations of the fault on their basis.

The algorithm of the separate surfaces' method involves:

- Creation of separate triangles on both sides of the step.
- Enlarging (extrapolating) both surfaces using the Kriging method, so that the entire fault is inside these surfaces.
- Projecting (assigning the elevation) of the upthrow side based on the upper surface, and the wing projected based on the bottom surface.
- Calculation of the projection over the entire length of the fault, checking whether the projection is fairly constant and consistent with predictions. If this is not the case, correctness of the input data needs to be checked.
- Cutting both surfaces to the fault.
- Combination of both surfaces and both fault lines (top and bottom) into one unit.
- Deletion of the triangles lying inside the fault.

#### 6. The method of extending the neighboring surface

It often happens that there is a lot of data on one side of the discontinuity line and not much on the other. The order of the procedure is then as follow:

- Creation of the seam floor surface on one side.
- Enlargement of this surface using the Kriging method, so that the entire fault lies inside of it.
- Projection (calculate elevation) of one fault wing based on this surface.
- Inserting a parallel line to the fault at a short distance and subtracting the fault throw from its elevation.
- Creation of a seam floor surface based on this calculated line and data on one side (Figure 5).
- Enlargement of this area with the Kriging method to the required range.
- Combination of both surfaces and both fault lines (upper and lower) into one unit.

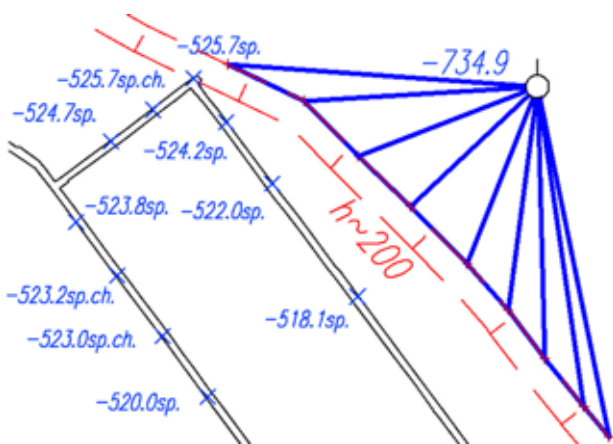


Figure 5. Inserting the fault with the method of extending the neighboring surface. Blue lines are the triangles based on the seam elevation (blue text)

7. Closed areas method

If there is only a little data available (geological boreholes and faults), we can create closed areas divided by faults. We accept one of these areas as fixed, and we raise or lower the remaining ones by the value of the expected fault throw (Figure 6).

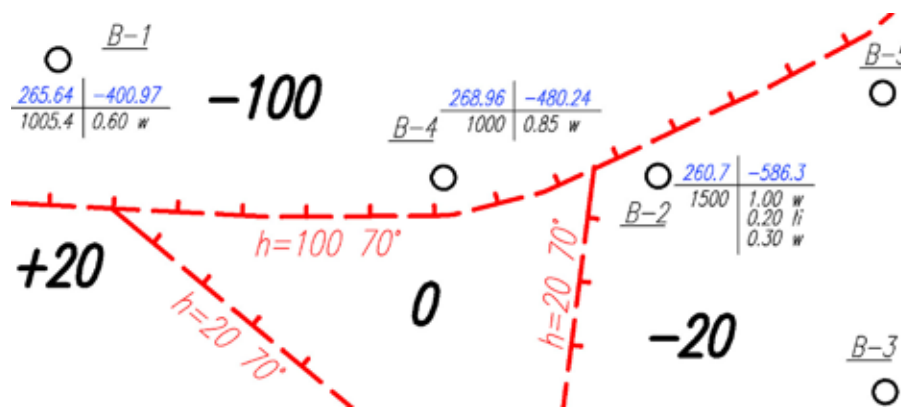


Figure 6. Dividing of the deposit into blocks along the discontinuity lines, which indicates the offset from the “zero” surface (black text: 0, -100, +20, -20). Circles with description are the boreholes (name, thickness, depth, and seam)

Thanks to this, we obtain one large surface, without faults, which is a representation of the situation as before the occurrence of tectonic movements.

The order of the procedure is as follow:

- Extension of the faults to the intersection with the borderline, so that closed areas are created.
- We accept one of these areas as fixed and, for others, we define how much they will be lowered in relation to it (Figure 6). It is possible to introduce faults with a variable inclination – then the given area will be unevenly displaced from the first one.
- Measurement data (seam floor elevation from geological boreholes), as well as the entire area on which data points are located, are lowered. If the faults have a variable inclination, then based on these faults, we create a reduction surface and calculate the reduction for each borehole separately – projecting it to this reduction surface.
- Based on the above data, we create one large surface without faults.
- Alternatively, we can edit this area, for example, additional lines can be added, such as the fold axis.
- By using the Kriging method, we extend the surface to the contour (border of the mining area). Previously, we could not use geostatistical methods because there was not enough data within the area between faults, i.e., one, two, or three geological boreholes, or even no borehole. Now we have at least a dozen or so – which already allows for a precise analysis of the course of the seam.
- We divide this one large surface into parts along the fault lines and lift it to its place.
- To check whether the faults have been entered correctly, we need to verify the floor seam elevation near the original boreholes.
- We cut the triangles inside the area with no deposit.

### 8. *Projecting to the surface method*

The simplest method of inserting a fault into the model is to project the fault line to the seam floor TIN surface. The algorithm for obtaining a fault by projection on the surface is as follows:

- In the first step, create the TIN surface of the seam floor only based on boreholes data, without taking into account faults.
- Project a fault line on this surface.
- Create a line parallel to the fault line at a short distance. The distance of the offset is calculated using the trigonometric function based on the throw and inclination of the fault.
- Raise the first line by half the throw of the fault, the second by lowering by this value.

Generally, the projection method is not recommended, because the generated seam floor (without taking the fault into account) may have an incorrect inclination. Sometimes, however, such an approach may be justified. For example, when:

- Accuracy is not important, when the model is only to be used to visualize the deposit and we do not make a final design of future exploitation.
- Faults are not detected, only presumed. Drawn approximately halfway between the boreholes, the distances between data are much larger than the throw of the fault. It is difficult then to obtain any accuracy and the selection of method does not matter.
- There is a large area without faults, inside which we have many geological boreholes. Then the procedure will be similar to the one described in point 6. We will only use boreholes inside this area to create the seam surfaces. After determining the course of the faults, in order to build the entire model, we will use these faults and all boreholes.

### 9. *Introduction of a discontinuity line in the solid method*

The deposit model can be presented in the form of a series of triangle grids (each coal seam separately) or in the form of a compact grid of cuboids imitating the entire rock mass. The solid method presents the deposit in a natural way, the most complex forms of deposit disturbance can be introduced into it. In this model, actual rock mass movements that affect all seams at once can be simulated. The disadvantage of the solid method is the time-consuming calculations and analyzes. In the mining geologist's work, where new data is received every day and we need

to quickly generate current isolines or a single-seam report, the triangle grid method seems to be better.

However, in both methods, the introduction of faults is quite similar: we need to predict where the fault begins, where it ends, and what is its throw and slope. Therefore, all the methods of determining the spatial location of the fault presented in the previous sections can be used in both methods. As repeatedly emphasized in this article, the most often given method is only the first approximation for the second method and an iterative (using both the solid method and the triangle grids) procedure enables an arrival at the most probable deposit model.

In Poland, in Jastrzębska Spółka Węglowa S.A., it was decided to use both methods interchangeably, depending on current needs. AutoCAD Civil with a Geolisp add-on software is used to apply the grid method. While the MineScape software was chosen for the solid method. An application was developed to exchange data between these two systems. A data format was developed, based on the csv text format, enabling the recording of geological borehole cards, seam thickness measurement points, fault locations, and chemical analyzes.

## Discussion and conclusions

This article describes the insertion of fault lines into a numerical model of the deposit, created as part of the system used in Polish hard coal mines. The presented solutions account for the specificity of the deposit in the region of the Upper Silesian Coal Basin, which is characterized by complex tectonics, and the occurrence of a large number of faults. Nevertheless, the presented solutions are universal and can be used in all types of mines, both underground and open pit mines.

In Poland, many hard coal mines have been operating continuously since the 19th century; maps contain thousands of faults and hundreds of thousands of measurement points. Accurate reproduction of the entire deposit would be extremely time-consuming and unnecessary. We usually make a model of the whole deposit in a very simplified way (Błaszczak-Bąk et al., 2018), while exploiting and planning for the nearest exploitation, the seam should be modeled in the most accurate way.

The main problem in creating the numerical model of the deposit is the very small number and low reliability of the source data. Therefore, the key is to check the deposit model and remove the assumptions and obviously incorrect data. It is true that the deposit can behave in a surprising manner, and we

cannot exclude even quite unlikely-looking situations in advance. Nevertheless, we should carefully analyze the places in which there has been a rapid increase of the fault throw or the intersection of the seams.

The scope of verification will be presented in the article “Determining the course of the fault in the entire rock mass and verification of the deposit model including discontinuity lines”. Based on geological data, with the appropriate software, we can develop a deposit model. However, we usually have too little data to allow the program to complete it in a mathematically exact way. For example, we have a dozen or so boreholes and a hundred faults; in addition, we are not sure of their throws or their position and location in 2D and 3D space. Nevertheless, an experienced geologist who knows his mine well has additional practical knowledge that can be used to create a model that is consistent with reality. To achieve this goal, the software used must be equipped with a simple option of manual modification of all parameters of the deposit. The most important elements presented in this paper are listed below.

The *Research methodology* section presented several original methods that allow for inserting faults into the deposit model. The developed algorithms were sorted, taking into account the number and type of input data available to the entrepreneur. Point 3 provided a method based on the assumption that the inclination of the seam in front of and after the fault is constant. This is the recommended method, especially if we are developing a small area, e.g., several exploitation longwalls with a dozen or so faults. The disadvantage of the method is the need to know the fault throw, and it is difficult to make manual changes in the course of the floor isoline.

Point 4 presented the method of calculating the spatial position of the fault based on existing contours that reach it from both sides. The advantage of this method is that we can shape the floor of the seam as required. This method needs previously generated contours, which is obtained by using a different method first. Point 5 described the method of separate surfaces. It consists of making independent seam floor surfaces on both sides of the fault. Then extrapolate both of these surfaces to the intersection with the fault. This is the most accurate method, and it is used wherever we have enough data.

The method of extending neighboring surfaces is used, when there is a lot of data on one side of the discontinuity line and not much on the other. In point 6, the algorithm of this method is presented.

Point 7 presented the method of closed areas. In this method, we attempted to obtain a rock mass that was before the occurrence of tectonic movements. This enables an application of geostatistical methods for all existing openings and correct extrapolation of the seam floor surfaces to the entire area that is being worked on. The disadvantage of this method is that it is time consuming to define closed areas, which is why it is only used if there are very few faults in a given area.

The simplest method of inserting a fault into a model is to project the fault line to the surface of the seam floor, as described in point 8. It is less accurate than the methods described above, and it is used when the deposit model is only for illustrative purposes. Currently, in geological programs, the solid method is often used to present the deposit model, in addition to the surface grids method. The methods of determining the spatial location of the fault presented in the previous points can be used in both methods, which was discussed in point 9.

The methods listed above are usually combined, the result of the first method is the input data for the other. By controlling and changing the course of the fault in the whole rock mass, we gradually arrive at a satisfactory result. It should be noted that the proprietary software Geolisp has tools to implement the faults according to the algorithms described, which significantly improves the process of model implementation. If there are not many faults, or we do not care about great accuracy, then generating a surface with faults is almost automatic. Even if the seam has a very complicated structure, we are able to develop a numerical model within few days.

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**Cite as:** Sokoła-Szewioła, V., Poniewiera, M. (2022) Methods of introducing a discontinuity line into a numerical model of a hard coal deposit. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 71 (143), 81–89.