Verification of the deposit model and determining the course of the fault in the entire rock mass

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Abstract
This article presents results for the development of new methods of inserting discontinuity lines into the numerical model of the deposit in CAD systems. The main problem in creating a numerical model of the deposit is usually a very small number, as well as low reliability of the source data. Hence, the authors developed new algorithms for inputting discontinuities, which can be used in particular for conditions when a large number of discontinuities are present. The article offers algorithms for inputting discontinuities into the entire deposit model. The method of transferring faults from the higher seam to subsequent seams and determining the course of the fault in the entire rock mass has been described. The fault can be represented as a spatial mesh of triangles, just like the seam floor. Then the fault can be extended until it intersects with the next seam (with the next triangle mesh) using geostatistical methods. As a result, we determine the exact position of the discontinuity line in the next seam. The paper also presents several algorithms for checking the deposit model made using the methods developed by the authors, including the analysis of outliers (in terms of elevation and inclination), testing the variability of the fault throw, checking the distance between adjacent seams, and verifying the position of the deposit in relation to the existing workings and boreholes. It should be noted that the key issue while building a deposit model is a checking of the model, removal of the assumptions and, obviously, incorrect data in order to obtain the highest possible accuracy.

Introduction

When creating a numerical model of a deposit, one of the most important problems we face is the insertion of discontinuity lines. The problem is particularly important when there is a dense mesh of discontinuity lines and the amount of data allowing for their input is limited. Therefore, in order to enable the implementation of this type of tasks, the Silesian University of Technology developed proprietary methods of inputting discontinuity lines into the numerical model of the deposit, i.e., the method based on a calculation of the spatial position of the fault involving existing contours that reach it from both sides, which includes the assumption that the inclination of the seam in front of and behind the fault is constant, an implementation of the independent surface of the upthrow and downthrow side with the Kriging extrapolation method, the transfer of a fault from a higher lying seam or the Carboniferous strata, and the method of closed areas. These methods were implemented in the Geolisp program

within the CAD system (Geolisp, 2022). They are presented in detail in the article "Methods of introducing a discontinuity line into a numerical model of a hard coal deposit".

Important works in this field was developed in different parts of the world: in China (Wu & Xu, 2003; Wu, Xu & Zou, 2005; Zhu et al., 2006; Jia, Li & Che, 2020), Pakistan (Jiskani & Siddiqui, 2019) and Poland (Jelonek, Poniewiera & Gąsior, 2015, Sokoła-Szewioła & Poniewiera, 2019). It should be noted that the problem is very complicated, and its solution depends most of all on the geological and mining conditions in a given area. It is of particular importance in the case of many years of underground mining operations, where data is available in the form of maps containing thousands of faults and hundreds of thousands of measurement points.

Accurate mapping of the entire deposit becomes extremely time-consuming. Hence, this article presents a procedure that significantly speeds up the construction of the model. It was proposed to adopt a solution in which a simplified model of the entire deposit is developed, while the areas of current and planned exploitation are developed with maximum available precision. The developed method is based on generating the surfaces of the underlying seams based on the surface of the first seam floor (including faults, folds, and other disturbances). The algorithm for carrying out this task is conducted in several stages. In the first stage, the surfaces of differences between the seams are generated, in the second stage, large faults are transferred to the next seams located below, and then small faults are transferred to the next seam.

The subsequent part of the article presents the scope for checking the deposit model, developed with the use of the algorithms proposed in the articles, with particular emphasis on the course of the inserted discontinuities. The checking includes an analysis of outliers (in terms of elevation and inclination), testing of the fault throw variability, checking of the distance between adjacent seams, and verification of the position of the deposit in relation to the existing workings and boreholes.

Research methodology

Determining the course of the fault in the entire rock mass

1. Generating the surface of differences

Seams are not at a constant distance from each other, they can merge in one place and disappear in another. However, we have a series of geological boreholes and in each of them is the vertical distance between the seams. Based on this data, we create an area of triangles that allows for the determination of the distance between seams at any point.

It should be noted that some boreholes do not occur in all seams. In addition, we have elevation data points that appear only on one seam. For example, if a single floor elevation measured in the exploratory working lowers a given seam by a few meters, all seams from the top and bottom have to take this depression into account, otherwise they will cross. In order to properly create all the seam floor surfaces in the rock mass, virtual geological boreholes should be inserted, which will cause subsequent seams to be more or less parallel and will not intersect. When creating the surface of the differences, it should be noted that the seams may have different names in different openings, e.g., when the seam splits into several layers: 401/1, 401/2, 401/1 + 401/2, and 401. It is convenient to divide such a seam for two or three separate layers and its thickness in a given borehole spread equally between all layers.

Of course, all these activities involve inserting virtual boreholes and assigning thickness, and it must happen in a fully automated way and according to defined rules. This has to be so because new measurements are made every day in the operational mine, and the model of the deposit must be automatically updated in accordance with most recent information of the deposit.

The algorithm for generating the difference surface includes:

- Creating the surface of the first seam, preferably the one that is best recognized.
- Constructing the surface of the triangle for the differences between the next seam and the first seam. We extrapolate it to the border of the area and use the ordinary Kriging method. Each borehole is checked and also the elevation points in the current and following seam. If any data does not exist in the first seam, we calculate its value by adding an interpolated point from the surface of differences.
- Again, we generate the first seam taking into account the added borehole. Moreover, the next seam is created. These activities are repeated until all the boreholes have a complete set of floor elevation data for all seams.
- From the surface of the differences, the boreholes are removed which in the given seam are located inside the fault zone or on the other side of

the fault. Theoretically, we could include such openings by subtracting the throw of the fault from the elevation of the seam floor. However, but we know the fault throw only roughly and it is safer just to delete such a borehole. We must use the iteration for this – several times repeating the above-mentioned activities because the surface of differences is made in order to obtain the position of the fault. Only after its determination can we see which openings should be removed. Removing these boreholes changes the position of the fault and the whole procedure should be repeated.

- The added boreholes should be completed with a seam thickness. Based on all the openings in the given seam, the surface of thickness is made. We extrapolate it to the border of the area using the ordinary Kriging method. Where the borehole passes through the seam, we enter a thickness of 0.01 (we can zero this, but one centimeter does not change the calculations and at first glance we see that the borehole is added). However, where the borehole was not deep enough, we calculate the thickness based on the thickness surface.

2. Large faults transfer to the subsequent seams

Usually, the largest problem we have is the insertion of a fault into the first seam. The following procedure can be applied to all seams at the same time, although the authors propose to apply it for subsequent seams. The discussed algorithm is automated to a certain extent (Figure 1), the user does not perform all activities, however, some verification activities should be done manually on each seam separately.
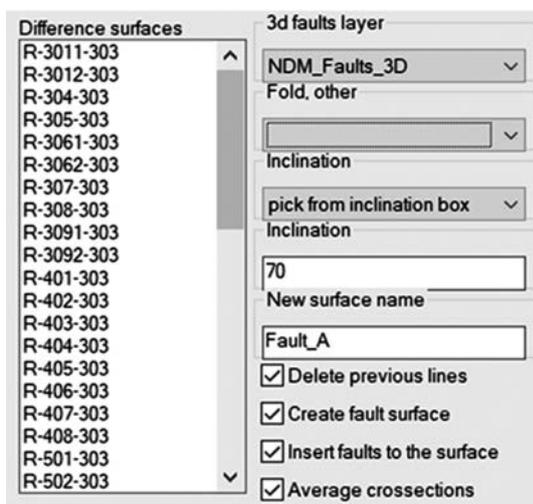

Figure 1. The application dialog box used to transfer faults to the subsequent seams

The algorithm of transferring the fault to the subsequent seams involves:

1. Texts and faults binding, so that descriptions and possibly other elements of the map move along with the movement of the fault lines on the map. In practice, in the described applications, this is done by inserting points at the ends of the selected objects, e.g., folds. Next, the program saves the position of such points relative to the faults and, after changing the position of the fault, it updates the location of the points and these objects.

2. Conversion of 2D faults into 3D, which means assigning elevation data to the lines on the numerical map. This can be completed using one of the methods presented in the article "Methods of introducing a discontinuity line into a numerical model of a hard coal deposit". The result of such an operation is the seam floor surface containing faults.

3. Generate a dense network of seam floor isolines, e.g., with a 10 m pitch. They are not necessary for the correct transfer of the fault, but they facilitate all verification activities and allow for manual corrections to the created deposit model.

4. Move faults to the next seam. In practice, this means inserting a new line more or less parallel to the existing fault (precisely speaking to the trace of intersection of the fault with the first seam). The new line will mark the intersection of the fault with the next seam. The distance between the trace of fault in the first seam and the trace in the subsequent seam will depend on the inclination of the fault and the distance between the seams. The distance between the seams is different at each vertex of the fault line – it is calculated based on the distance surface, which is determined in point *1 – Generating the surface of the differences.* The result of the program operations is shown in Figure 2.

5. Verification whether the fault lines pass through confirmed fault locations (i.e., in exploratory workings). If not, it means that the inclination
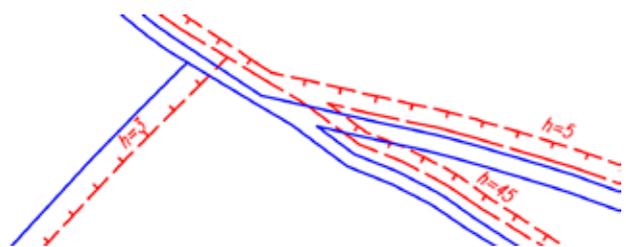

Figure 2. Red lines represent trace of the fault in the first seam, while the blue lines depict the fault intersection with the next seam

has been selected incorrectly (or there is another mistake, e.g., wrong fault throw). The new slope must be recalculated using the trigonometric functions, assuming a linear course between confirmed points. If data has been changed, activities described in point 4 must be repeated. In some seams, the fault disappears and splits into several smaller ones, it is then difficult to determine its position automatically. In this case, trace of the fault in the given seam must be inserted manually.

6. Verification of intersection points of new faults. The algorithm moves each fault separately and the result sometimes is not correct, especially if two faults are close to each other. In the lower seam they should merge into one fault, but the program will draw two intersecting lines. In this case it is required to review and correct the location of the fault intersections manually.

7. Move the isolines created at the stage described in point 3 to the new fault lines. Other lines like disturbances, folds, and seam merge lines should be moved too.

8. From the elevation of the objects obtained in point 7, we subtract the surface of elevation differences determined in accordance with the algorithm presented in point *1 – Generating the surface of the differences*. As a result, objects such as isolines, folds, and faults intersection points receive the elevation of the subsequent seam.

9. The faults obtained in stage 4 are spatial lines; however, in practice it is better to recalculate them – from the isolines obtained in point 8 – using the existing contours method.

10. Create the surface of the seam floor taking into account all data, including isolines and faults created in the above paragraphs.

11. Verification of the faults throws, distances between neighboring seams, the inclination of each triangle, etc. (see next section). If, as a result of the verification, it turns out that there is a significant error in data, then the whole procedure starts from the beginning.

12. Moving descriptions of faults and other objects, as we planned in point 1.

13. Commence construction of the triangles surface of the next seam. The presented method may look complicated, but in practice the construction of the next seam does not take more than a few hours.

3. *Small faults transfer to the subsequent seam*

Large faults cross many seams, their course is reasonably predictable since the rock mass moves along fairly steady surfaces. However, small faults sometimes occur only in one seam, disappear, and then re-appear in the lower seam. Rather, we can talk about a zone of a cracked rock mass, where the course of the fault cannot be predicted in any way. The decision on which fault is large, and which is small is arbitrary and depends on the geologist developing the deposit model. Usually, we define the limit value of the discharge, e.g., two meters, below which we consider the fault to be small. Yet, if a given fault occurs in several adjacent seams, we include it in the model even if the discharge is smaller than assumed. However, such faults cannot be completely ignored, because their occurrence is important information for engineers designing new exploitations. The procedures in this case may be as follow:

• Copy small faults to the next seam, as if they were vertical, then insert them at the same place as in the previous seam.

• Project these faults to the surface of the floor of the subsequent seam.

• Assign a zero fault throw value. It is not necessary to insert them into the deposit model. Inserting them unnecessarily complicates the model and increases the time required for all calculations. But on the other hand, we receive additional information in a spatial view; we see small triangles, so we can observe that something is happening in this position. In any case, we must remember that these faults must be transferred to all paper documentation.

• Small faults are transferred only to the nearest seam from their appearance. Only the large faults are transferred to the subsequent seams.

4. *Presentation of the fault in the form of the surface of triangles and its extrapolation*

The fault can be presented in the form of a surface of triangles, just like the seam floor. This is the most recommended method for controlling the model of the deposit. The way of creating and controlling the surface of the fault is presented in the next section. Just like the seam floor surface, the fault can be extrapolated using geostatistical methods.

Hence, the solution is to cross the surface of the fault with the seams generated based on geological boreholes. This method is simple and fast, the option "Insert faults to the surface" of the program (shown in Figure 1) works according to such a procedure.

The algorithm for finding the intersection of seams with a fault surface involves:

• Based on the boreholes, create a surface of triangles for each seam floor separately.

- Extrapolate these TIN surfaces to the boundaries of the mining using geostatistical methods.
- For each seam, create a volumetric surface area consisting of the surface of this seam and the surface of the fault.
- The intersection of the seam and the fault will overlay with the isoline zero of the volumetric surface.
- Find the second trace of the fault (the end of no deposit zone) corresponding to the method of extending the neighboring surface.
- Next, successively create TIN surfaces for the floor of all seams, each of them based on geological boreholes and both fault traces (Figure 3).
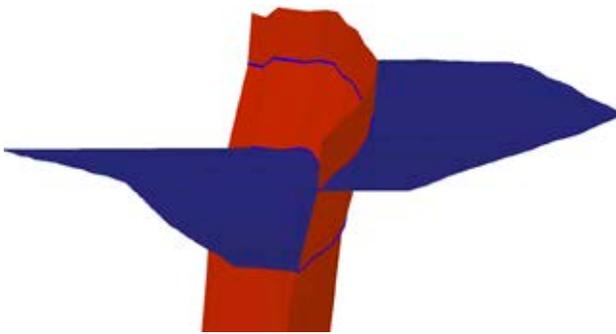

Figure 3. Intersection of a seam floor surface (blue) with the fault surface (red)

If a fault throw is unknown, it is determined from the following procedure:

- Insert a line between adjacent boreholes, one (A) inside the area where there is a lot of data, the second (B) outside of this area.
- Project this line to the seam floor surface created from data inside the main area. Using the linear interpolation method (if there is a lot of data, we can use geostatistical methods), extrapolate the elevation at the location of the borehole B. The difference between the actual elevation of borehole B and the one calculated will be the value of the fault throw in this position.
- Proceed similarly for the next pairs of geological boreholes along the entire length of the fault. We assume that the throw of the fault in the other cases bends between the boreholes calculated in the pair's changes in a linear way.

Verification of the deposit model

The scope of the verification includes the following stages:

1. Generating isolines of the seam floor. Analysis of the course of isolines to check whether they

overlay with the original isolines, are parallel to each other, reach a right angle at the fault, do not disturb near the geological holes, and the change of inclination is smooth (Figure 4).
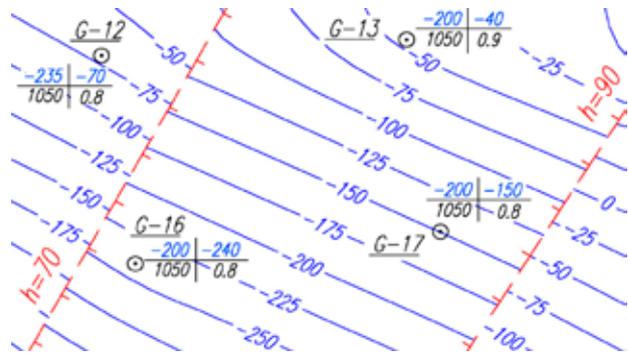
Figure 4. The course of the seam floor isoline next to the faults and boreholes

2. Prepare a series of cross-sections through a rock mass. On the cross-section, we can see if the subsequent seams cross or are parallel to each other. If the workings are located on the cross-section, it must be checked whether in these workings the passage through the coal seam was actually observed.
3. Check if the floor elevation of the triangles is exactly the same as the value from the borehole. The article omits issues related to the selection of surface smoothing coefficients using geostatistical methods. However, it should be mentioned that, for example, an incorrectly chosen nugget effect can cause the inclination of the seam to change rapidly near the borehole. It is easy to find out this error by analyzing the course of the contours near the borehole.
4. Generate a volumetric surface between each pair of seams. The isolines of the volumetric surface indicates the vertical distance between these seams. If there is an isoline of zero, it means that the surfaces intersect. The distance between the seams should not change rapidly, the isolines should be parallel to each other.
5. Create an additional surface of the triangles of the floor inclinations. Check every location in which the inclination of the seam has an unusual value. If the seam in a specific location has a very large slope, it usually means that we have not removed the triangle from the center of the fault.
6. Calculate the inclination of the fault line in the seam in each triangle separately. Changing the inclination of this line should be done in a smooth way. Similarly, check other lines that build the

deposit model, e.g., the fold axis or the seam merge line. The discussed software has the function of marking all locations in which the inclination is greater than is given.

7. Calculate the fault throw along its entire length. Similar, to the previous point, the change of the fault throw should occur in a proportional way. The software draws graphs of the change in the throw of the fault, which allows the wrong location to be quickly spotted (Figure 5).

Figure 5. Graph of the change in the throw of the fault

8. Examine the model of the deposit and check the isometric view. Usually, it is possible to capture positions where, e.g., faults intersect in an unlikely way.

9. Check the floor surface near the boundaries of the developed area. If the surface of the seam floor is cut by faults, it cannot be extrapolated using geostatistical methods. One of the possible solutions is an attempt to restore the surface from before the occurrence of tectonic movements. As a result of such an operation, we obtain one large surface, without faults, which we can extrapolate to the boundaries of the area, e.g., by the ordinary Kriging method. Verification consists in making a cross-section through a rock mass and checking the changes in inclination near the boundary of the area.

Discussion and conclusions

This article presents the problem of inputting a discontinuity line for the case of long-term underground exploitation of hard coal deposits, such as in the case of the Upper Silesian Coal Basin; in this area, industrial exploitation has been carried out since the 19th century. The time-consuming nature of developing a numerical model of the deposit under such conditions was indicated. A solution has been presented in which a simplified model of the entire deposit is developed, while the area of the

currently conducted and planned operation in the near future is performed with the maximum available precision.

It should be noted that the development of the floor of the first seam (containing the faults, folds, and other disturbances), from which we start building the model in the proposed solution, is presented in the article "Methods of introducing a discontinuity line into a numerical model of a hard coal deposit". Next, in accordance with the proposed procedure, we create volumetric surfaces (TIN surfaces of distance differences) between all analyzed seams. Knowing the size of the fault throw and its inclination, fault traces for all the seams are determined. In the last stage, the course of small faults in the next seam is determined.

An absolutely key issue for the correct development of the deposit model, especially in the presence of the discontinuities, is the checking of the deposit model and the removal of assumptions and obviously incorrect data. It is true that the structure of the deposit is often very complicated, but it is recommended, however, to carefully inspect the model in such locations where sudden change in the fault throw or seam cut is observed.

This article presents the scope of the model checking, which includes activities enabling the verification of the correctness of the isolines course, the generation of a volumetric area between each pair of seams, the calculation of the fault inclination in the seam (separately for each triangle) and along its entire length, the verification of the position of the deposit in relation to the existing workings and boreholes etc.

It can be stated that the algorithms developed at the Silesian University of Technology allow for the insertion of discontinuity lines to the numerical model of the deposit in CAD systems. They make it possible to reduce the time-consuming nature of building such a model, while ensuring the highest possible accuracy of the model, with a specific range of data available. The authors presented a number of procedures that enable the control of the work performed to achieve a high accuracy of the model.

Future works on this solution may be related to a new heuristic architecture for production line management in JSW S.A. (Jastrzębska Spółka Węglowa) (Dyczko, 2021). The identified small amount of data to some extent confirms the thesis about the need to expand the scope of collected data in the mining map proposed in other works (Krawczyk, 2018).

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