

Volume analysis of open-pit mines on the basis of photogrammetry principles

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Abstract: The volume analysis of open-pit mines is important for preparing the plans for environmental recultivation. To assess the predictability of finances and deadlines it is indispensable to determine the exact amount of backfilling required. A geodetic survey presupposes a very time-consuming and special expertise; furthermore, accuracy depends on the experience of the expert and on the number of conducted surveys. Drones can take aerial photos, from which a surface model can be produced. The survey requires a short amount of time, depending on size, 10 to 40 minutes/0, 5 to 10 km². In the cases shown, the amount of backfill material was determined by the help of a photogrammetric method after the successful 3D model creation of many artificial buildings. In case of mines, cover surfaces have been developed from many viewpoints, with the help of which the scale and the manner of refilling can be optimized. The finished method may become an effective alternative to traditional surveys.

Key-Words: UAV, 3D surface model, photogrammetry, recultivation, surface generation, volume calculation

1 Introduction

Aerial photography done by the use of unmanned aerial vehicles (UAV) can substitute conventional aerial photography done on airplanes. In case of UAV flights, surveying areas of a few square kilometres (~10 km²) takes 20 to 40 minutes depending on the type of the aircraft. After the subsequent photo processing the orthonormalized and pieced together photo's available resolution is still (10-14 megapixels) 3-3.5 cm/pixel even by using ordinary cameras. During the photo processing done by overlapping (60% overlap of all edges is expected) a 3D surface model can be made, apart from the most used orthophoto. According to our survey experience, depth accuracy is 10 cm better in case of shots taken from the height of 150 m by fixed-wing UAVs. This accuracy can be improved, even to 2-3 cm with multi rotor aircraft, specifically in case of taking photos of a near (3-5m), smaller objects (a building, monument, etc). If

topographical reference points are located in the area, which is under survey, or tested reference points have been set prior to the shot, there is a possibility of orthophoto and 3D surface model georeferencing. Measurements can be carried out on the georeferenced pictures. The measurements' accuracy corresponds to the figures above. As the depth data are georeferenced as well, the airspace of spatial formations (hills, ditches) become measurable. The results of 3D surveys can be used in many areas of database systems. These areas include the archiving of the momentary state of certain formations, the establishment of virtual museums for buildings, monuments and architectural relics, the inspection and documentation of real estate investment processes, the documentation for public utility locations, the production administration of open-pit mines, the survey and documentation of closed open-pit mine recultivation. The volume analysis of surface objects can be particularly useful from the aspect of

environmental protection. The recultivation of closed open-pit mines is, in many states, a legal requirement. This question in Hungary is regulated by the mining law [1]. To determine the amount of backfilling material required for the recultivation, the 3D surface model can be used, created from the UAV photos. In case of using proper software it is not only the amount of necessary backfilling material which can be determined but also the architectural design of the eventually recultivated area. In advance, calculations can be carried out for the formation of various surfaces, which make it possible for specialists, who take both geological and economical aspects into consideration, to develop the optimal solution (the amount of backfilling). This essay elaborates on the problem area outlined above, as well as on the results of practical tests carried out in this field.

2 Survey with help of LIDAR

LIDAR (Light Detection and Ranging) is a device for measuring distance, which works with active signals. In these devices the survey is conducted based on emission and reflection. It emits signals in the ultraviolet, visible and infrared regions. It is a commonly used survey device at open-pit mines.

The laser emits an energy impulse that interacts with the objects, which are in the direction of the spread. The impulses reflected by the object hit the sensor of LIDAR, in this way the time between emission and reflection becomes measurable. The impulses, which are not reflected by the first object, can return from other objects, which lie farther. In this way the device can measure the distance of more objects at the same time – although this presupposes a more developed device.

2.1 The problem with LIDAR

LIDAR devices are typically terrestrial, manual devices with a tripod. These devices measure objects, which have clearly defined edges, are above the surface of the terrain, are accessible, walk around, for example piles, which were created in the process of extraction. During the survey, measures are taken from many angles and after the algorithmic processing of these the surface model of the object can be given. In this way volume can be measured. The problem has two origins:

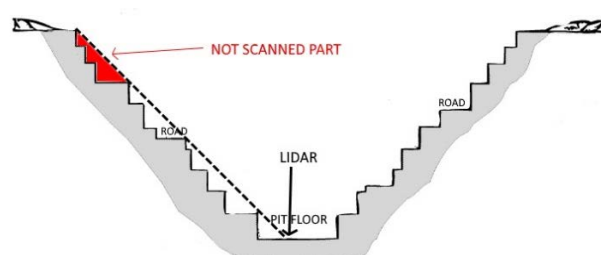
1. In case of sufficiently big and high objects during the walk around, only the side cover surfaces can be surveyed, it is not possible to survey the top

cover surface. In this way, only by connecting the sides can the survey be inaccurate.

2 In case of open-pit mines the survey of the extraction area can be conducted in different ways:

- a. around the extraction area, by surveys conducted from the edge of the mine, which can cause connection problems

- b. by the device, set up at the bottom of the extraction area. In this case the problem of blocking has to be confronted: certain smaller, bigger cuts, artificially created roads, for the purpose of helping the production, and the supporting embankments of those block one side of the road's rising part, in other words, the survey dataset will be incomplete, containing holes.



It is a general problem with the LIDAR based survey of open-pit mines that the expert entering the working area does not necessarily know how the mine operates, and this is precisely why the operation of the mine has to be limited or it might even be necessary to shut it down.

Besides using DAR, the survey based on photogrammetry can be a good alternative, which is cheaper, similarly accurate, faster and does not disturb the operation of the mine.

2.2 The more effective use of LIDAR at open-pit mines

A solution for the above mentioned problems could be if we hang the survey device above the middle point of the extraction area, or even if it hovers. The survey conducted in this manner can be much more detailed, every part of the mine can be seen, there is no or minimal amount of blocking.

3 3D model creation based on the principle of photogrammetry

The basis of 3D model creation is that a few, somewhat different pictures, taken of the same part of the terrain, must be available. This prerequisite is fulfilled when, in practice, we take such aerial pictures, in case of which we ensure the overlap between the pixels in a way that all of the rendered

pixels are at least in two pictures (in case of special edge conditions). In practice, however, the same pixel has to be in more pictures than that. If the spatial location of the taken photo and the direction vector of the camera's optical angle are known, a line can be determined which pierces through the projection plane and determines the given pixel in the projected image. If this pixel can be found in another picture then another line pierces through the projection plane but the piercing point of that does not match the piercing point of the previous picture's projection radius, apart from a few special cases. This is possible because the same pixel from another point of view is seemingly situated at another place. At the same time, the two projecting lines, intersecting each other, determine a point outside the projection plane, which corresponds to the spatial position of the concerned pixel.

To determine the projection radii the two fundamental prerequisites are: to know the accurate position of the capture and the optical axis of the camera, and to know the pixel pairs in the overlapping photos (identical pixels). The position of the capture can originate from the sensory system built into, or integrated into the camera. This sensory system fundamentally means a unit summarizing the data of GPS (Global Positioning System) and IMU (Inertial Measurement Unit), and providing orientation. These data can be determined by the visual information of the captured photos. Given that the pictures are inevitably made with significant overlap on account of the reasons outlined above, the camera's optical axis and its spatial position can also be determined by the analysis of the photo content. If we assume that the picture's pixel centre taken from a geometrical point of view is undistorted in each and every picture and we consider this as the reference point between the pictures then we can find such, special, pixels in positions different from this, which can be found in many photos as well. The distance of these pixels, in reality, does not differ from the reference point, whereas in the pictures it is different. This difference becomes the measurement of perspective distortion, which makes it possible to determine such a transformation, which gives the spatial position of the picture's capture. The method can be automatized well, but its condition is that a visual content must be available, in which these above-mentioned pixels can be determined well. These may include corner points of buildings, roads or other distinctively separate crossroads, etc. The method cannot be used on homogenic pictures, such as water surface lacking ripple and structured reflected pictures.

From a practical point of view, in case of surface objects' examination, fortunately, in the vast majority of cases articulate and high contrast structure provides sufficient reference points.

The connection between pictures is provided by identical pairs of points. The identification of these point pairs can also be automatized in the similar way to determine the position of the picture. The basis of locating point pairs is that we must find such, so called, corner points in the pictures that are separate from the other pixels. These are pixels found on the boundaries of characteristically strong intensity changes, for example, edges of buildings, borders of forests and highways. Certain attributes can be assigned to these points, such as the intensity gradient, and/or the intensity distribution of neighbouring pixels. Numerous corner point detecting algorithms can be used for this purpose. Of these, one of the most widespread is the "Harris algorithm". If these attributes are invariant for the zooming and rotation of attributes then there is a possibility for finding corner points of a similar attribute in the overlapping pair of pictures. Similarly for detecting corner points, numerous algorithms exist for determining pairs of points. SSD (Sum of Squared Difference) is one of these. The corner points found and paired in this way are to be refined by further filtering algorithms, because in processing at this point there are many faulty pairs of points in the system. One of the most well-known filtering methods is RANSAC (RANDOM Sample Consensus).

By the application of the above mentioned algorithms a spatial point cloud can be produced which corresponds to the discrete set composing the surface of the recorded space. A continuous surface model can be made by connecting the points to each other. Of course, during the surface model's formation many algorithms can be utilised as well. One of the most well-known algorithms is the Delaunay triangulation. As a result we get a surface model covered by triangles. During the surface model's formation such special morphological filters can be used, which contain presumptions characterising terrain conditions. With these filters the unrealistically outlying elements can be refined.

If the position of the capture location is not determined by GPS but the visual content, the produced surface model is not yet adequate to carry out quantitative measurements. For this purpose georeferencing of the established database is required. The prerequisite of georeferencing is that the original area must have geodetic reference points or easily identifiable, accurately measured reference points in the picture which were made

prior to taking the photo. It is a less accurate method if the coordinates of the easily identifiable objects are determined by the help of other databases, such as Google Earth. As a result of georeferencing a measurable 3D object is created, which can be placed in the world.

For the processing of overlapping captures there are finished systems, which provide all of the features, which have just been outlined. They also produce a 3D model of the surveyed area semi-automatically. Such software system is, for example, Agisoft PhotoScan.

3.1 Managing 3D Model errors, closing objects

If the object's 3D model is produced of 2D photographs, continuity errors are quite often made. One of these types of errors refers to the closing of the objects. Some parts of the object's surface may be torn, in other words, plainly, there is a hole in it. A hole can be defined by a series of edges, which only have a face on one side. One or more missing parts produce one or more holes in the object. Because these are usually small errors their management can be automatized in an algorithmic way. Automatic troubleshooting in the vast majority of times does not produce visible change on the object, thus during later examinations and calculations significant errors are not to be counted with. The removal of holes is, however, indispensable from the aspect of further processing. For the solution of this problem almost all of the 3D programs provide tools. The aim of algorithmic troubleshooting is the removal of holes by inspecting the whole spatial network in a way that the object becomes closed with the smallest surface change. Autodesk 3ds Max is a program which has this feature. The parameters of the software's troubleshooting module can be set. Among these parameters one of the most important is that the filling surface, which is used for troubleshooting, should fit to the object's already existing surface. Numerous analyses and measurements can be carried out on the closed object. Some of these are the object's size along X, Y, Z coordinates, the area of its projection given by the user, its volume and the coordinates of its virtual coordinate system's midpoint.

4 Surveys of artificial surface formations

During the photo shoot of an area, where mostly the aim of processing RAW images is to create the

area's orthophoto, an elevation model can be made. This elevation model can be used for the 3D reconstruction of the given surface.

Generally, the size of the surveyed areas presumes the use of such aircraft, which is capable of flying a pre-planned route autonomously, as well as taking pictures. This is necessary because the operator is not able to fly the boundaries of the areas safely. For this telemetry data are necessary, which can be used to inspect the momentary position of the drones. As practice shows, telemetry information is indispensable for the capture of photography, because immediate intervention in flight, if necessary, can only be ensured in this way. Flights should be done autonomously.

The advantage of autonomous flying is that the flight of the target area can be planned beforehand. Knowing the type of the camera, a flight route can be planned, which ensures the necessary minimal overlap between the captured frames. Experience has shown that during surface photography fixed-wing aircraft can be used efficiently. Their consumption, load bearing capacity and speed are beneficial as regards the surveys. Take-off and landing can be considered a small disadvantage, which requires a plain and an area free of terrain objects.

During the experiments a flying wing transport aircraft was selected with a take-off mass not exceeding 3000 grams. This aircraft could even be hand launched, but the rubber band launch was also easily applicable. Due to the small mass of the aircraft landing was easily doable as well.

The first step of the survey is the flight plan of the area intended to be surveyed. (Figure 1). The flight route must be planned in a way, that during parallel flights at least 50 percent lateral frame overlap must be ensured. A further criterion is that flight height must be set in accordance with aircraft speed, with the camera's lens and with its shutter speed, in a way that the lateral frame overlap between the frames must be at least 50 percent. The camera employed in the experiment is a Canon Powershot A2600, in which a special firmware update provides an automatic capture feature. In practice, lateral frame overlapping was around 50 percent, whereas longitudinal overlapping was around 80 percent.



Fig. 1. The flight plan of the area, where recording is intended to take place (Mission Planner)

The flight speed of the transport aircraft was 50 km/h, and the flight height was above 150 meters above the starting place. 682 pictures were taken during the flight, which meant 3 gigabytes of data.

The selected area is nearly 1600 meters long and 600 meters wide. The actual track of the flight can be seen in figure 2, with the capture position of individual pictures. Because all of the frames overlap generally 4, but at least 3, neighbouring frames, the capture location and orientation of the frames can be determined. Consequently, the spatial position of relevant pixels (those, which make up pairs that can be found in least two pictures) found in the pictures can be determined.

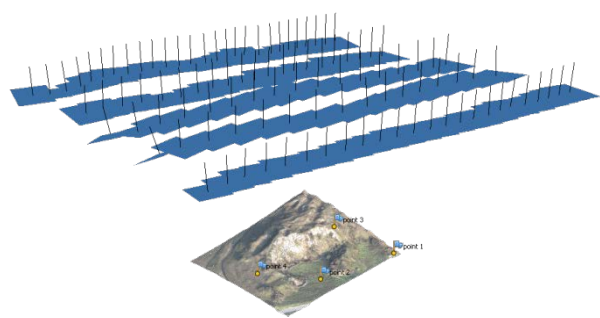


Fig. 2. The spatial positions and orientations of the pictures taken above the recorded area. (Agisoft Photoscan)

The spatial point cloud, created after the processing of the pictures, is triangulated by the program. These triangles make up the surface, which is the model of the already surveyed surface. Of course, the number of polygons, or in another way, the detail of the surface, can be determined here as well. The ready 3D model can be observed from optional viewpoints. The model only contains the surface, in other words the polygons covering the surface have no width. In a further step of

processing a texture can be fit to the 3D surface. The program creates the texture with the help of the orthophoto, made during the previous steps. Fundamentally, two models of texture fitting can be chosen. The easiest, but in case of surface models more practical, one is when the texture (figuratively, as a rubber membrane) is stretched on the surface model. The result of this method is that the vertical walls (if there are any in the surveyed area) are "painted" with the colour of pixels found on the edges. This method cannot be applied in case of buildings or characteristically vertical or concave surfaces.

During the rendering of the finished 3D elevation map, the actual 3D surface model is created and one or more (this depends on the size and articulation of the model) picture files containing the texture. A collection of these files is needed for the visual display of the picture seen in figure 3. The display itself can be provided by many programs. For example, MeshLab is one of these, which can be downloaded and used free of charge.

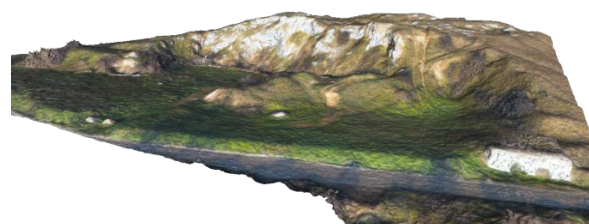


Fig. 3. The 3D display of a closed lime kiln and an open-pit quarry

5 Calculation of the amount of filling material required for the recultivation of a closed mine by 3D models

By the use of a mathematical algorithm a covering surface can be created, which might resemble the original, currently missing surface, which could be the result of natural erosion, and which bears a shape, which corresponds to the adversity (rainfalls, flows, etc.) that nature can create.

The first step to create the covering surface is to determine the edges of the surface by giving spatial points, which fit the edge of the mine wall. The points given in this way necessarily guarantee the direct connection between the mine and the covering surface. If more fitting points are determined the more accurate the fitting is. These points serve as the basis of the covering surface. It is worth choosing evenly spread points, because the algorithm will produce a surface on these. If the 3D model with the scale of 1:1 is imported, then there is nothing to be done with the coordinates of the

chosen points. On the contrary, it is necessary to recalculate the coordinates to the coordinates of the actual, 3D model, otherwise there might be problems with the fitting of the surface.

The necessary points must be selected manually, with the help of specialists by the use of software programs. For the display of this present solution the programs, Autodesk 3ds Max and the Matlab, have been used.

The chosen points can be selected by the MaxScript Listener window, by referring to their identifiers:

```
$.selectedVerts = #{136678, 101440, 94408, 87666, 82446, 76975, 124123, 127763, 25364, 139989, 138857}
```

The result must be similar:

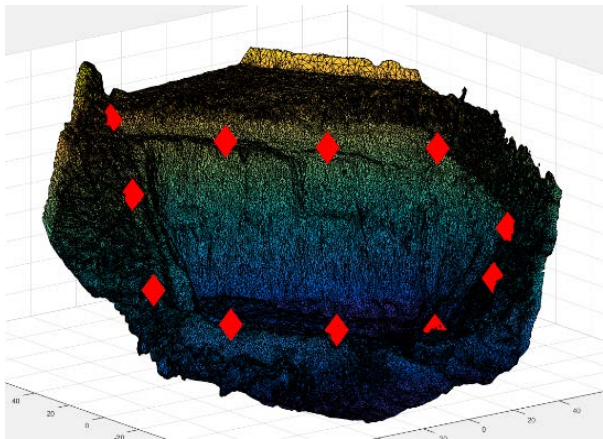


Fig. 4. Display of the chosen points

The coordinates of the points in the given coordinate system can be acquired with the command below:

```
in coordsys world polyop.getVert selection[1] vertex_azonosito
```

The table below contains the coordinates of the particular, chosen vertices

Vertex ID	[x,y,z]
136678	[-60.2346, 20.8849, 12.4835]
101440	[-37.5378, 60.9918, 23.37]
94408	[-21.9967, 94.8076, 31.8152]
87666	[14.1075, 74.9156, 27.142]
82446	[48.1863, 59.4043, 24.9682]
76975	[75.5893, 34.1708, 25.82]
124123	[76.5563, -4.50411, 15.128]
127763	[53.1449, -26.9167, 10.4494]

25364	[18.9581, -37.428, 5.1656]
139989	[-24.2446, -37.5131, 7.82067]
138857	[-52.8318, -15.4119, 9.27921]

Table 1. Vertex coordinates

With the knowledge of vertex coordinates a covering surface can be generated by Matlab with the help of the Delaunay algorithm.

5.1 Delaunay triangulation

The Delaunay triangulation is a widespread method in 3D modelling. The advantage of this method, which covers spatial formations with horizontal triangles, from the point of view of Spatial Information Technology, is that the calculated data can be fit to the vertex of any triangles. In this way, the necessary interpolations, which inevitably bring inaccuracy into the model, can be avoided in case of even grid resolution.

As during the processing the original object is also made up of a surface covered with triangles it is reasonable to build the mine's covering surface of triangles as well. The starting data of the Delaunay triangulation are given by the manually selected fitting points outlined above. Since these points don't change their values during the calculations, thus the created surface, and the volume counted from that, will contain the fewest conceptual error.

Figure 5 displays the covering surface of the mine, which was surveyed during the experiment. The calculations were made by giving 10 fitting points with the help of the Matlab program.

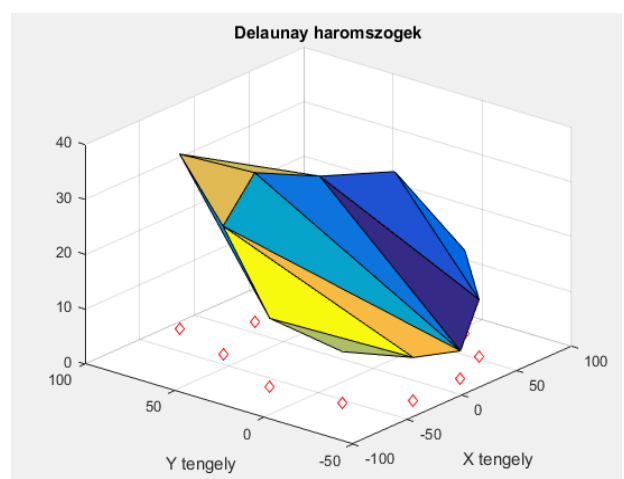


Fig. 5. Surface made by Delaunay triangulation

The details of the surface above is largely determined by the number of fitting points (reference points) chosen as starting points. Of

course, the increase of fitting points means relevant improvement in case of difficult terrain surfaces. Setting the above mentioned particular fitting points can be done by a layman, for example, evenly on the edge of the object, but a much better result can be achieved if the points are determined with the help of a surveyor. In the latter case, the experiences of the field can be automatically taken into consideration.

5.2 The production of a closed 3D object, adequate for volume calculation

Considering the fact, that as a result of the survey the surface model of the mine is only a “shell”, in other words, it does not have width, volume cannot be calculated from the data. The covering surface created by the method above is also a shell without volume. During the merging of the two surfaces a closed object is created, which has relevant volume. Two methods have been developed for the merging of the two surfaces:

1. Importing the original surface model into the Matlab program and merging it with the generated surface, then by exporting the merged object from here the .OBJ format model is created. In this case, following the importing of the surface model, choosing the fitting points needed for the covering surface, then creating the covering surface and the merging of the two objects created in this way are done within the software system. This creates a partly manageable, transparent, and user-friendly solution for the specialists carrying out the calculations. (figure 6).

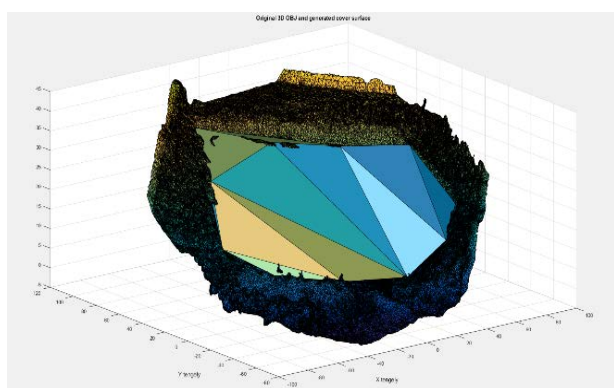


Fig. 6. The original 3D object and its covering surface

2. Only the exporting of the generated covering surface is done and the merging of the two surfaces (surface model of the mine and the surface model covering the mine) is made by the use of the 3ds Max program. The advantage of this solution is the

excellent visualisation ability of 3ds Max. With the help of this program the merged model can be easily rotated, thus the created model can be observed well at a visual inspection.

5.3 Volume calculation

The new 3D object, produced by the method reviewed previously, can be imported into other programs to carry out further calculations. 3ds Max is a program of convenient choice, which is capable of determining the volume of 3D objects. The calculated volume uses the measurements corresponding to the one given before importing.

The first table contains the volume data of the object of the mine, introduced in the experiment, covered with a generated surface made with the help of the Delaunay algorithm, in light of the various overlaps. Using points for the calculation, chosen at random, various surfaces can be generated. In respect of the first point cloud, they are originally chosen, compared to this, further point clouds differ in some principles, but they contain points close to some particular points of the original point cloud. In case of movement, it is defined by moving the points on one of the axes, whereas in case of rotation it is defined by the rotation of the points in accordance with one of the directions.

	Volume
Original mine model	~32.200 m3
With covering surface moved to the left	~31.500 m3
With covering surface moved to the right	~37.200 m3
Rotated covering surface 1.	~36.100 m3
Rotated covering surface 2.	~41.300 m3

Table 2. Volumes with different cover surfaces

As it can be seen, the basis points chosen to generate the surfaces have a significant influence on the attributes of the generated surface, thus on the volume of the covered object as well. In case of the differences visible in the table above, the height of particular points, interpreted on a axis Z, influenced the surface generating algorithm.



Fig. 7. Model of closed open pit mine

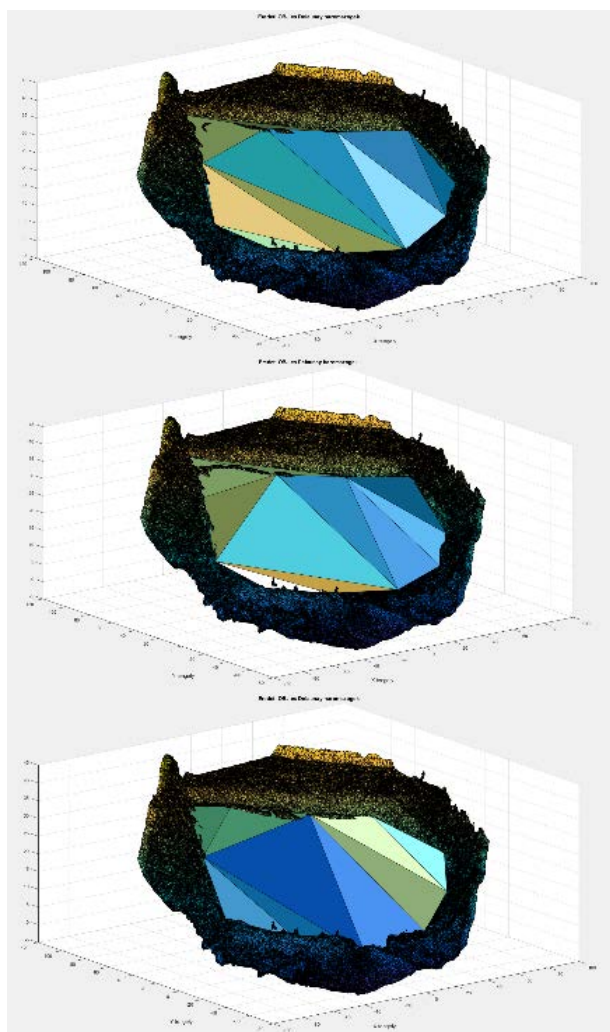


Fig. 8. Different Delaunay surfaces

5.3.1 Problems with calculating volume

Modelling programs available for the public are fundamentally acceptable for the volume calculation of 3D objects. Although the algorithms used by particular programs can easily make mistakes. One of the problems that can appear is that overlapping and intersecting “faces/triangles” produce mistakes in volume calculation. If the original model and the covering surface raised on it produce such overlaps

and intersections then the calculated volume must be treated with caution, and the results must be examined with numerous, but similar surfaces.

6 Results

During the experiments, high resolution orthophotos and 3D surface models have been made of numerous open-pit mines. The amount of required filling soil for the recultivation of the previously introduced, closed mine have been determined in accordance with many approaches. We have first inspected the calculation results by the help of 3D elevation models available free of charge, and for the sake of more accurate surveys, we have matched them with the volume data calculated from geodetic surveys carried out on the introduced mine. In all cases, the evaluations have shown, that during the landscaping, the results of volume calculation based on photogrammetry principles have been within the expected accuracy range.

As the calculation results showed adequate accuracy, this cost-effective, quick survey and calculation method can be an effective alternative of surveys based on conventional geodesy.

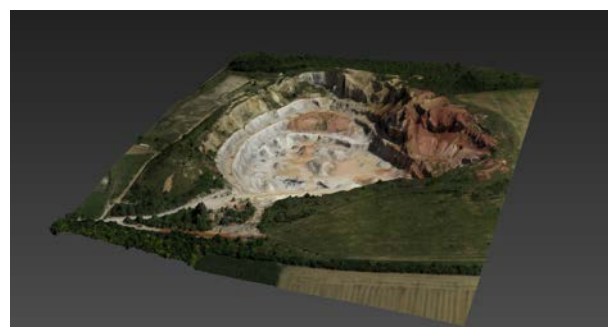
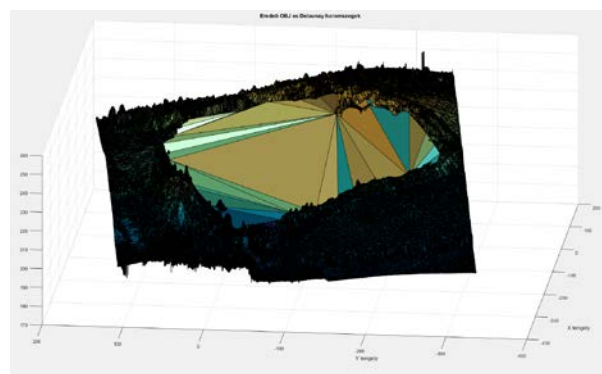


Fig. 9. 3D model of active open pit mine



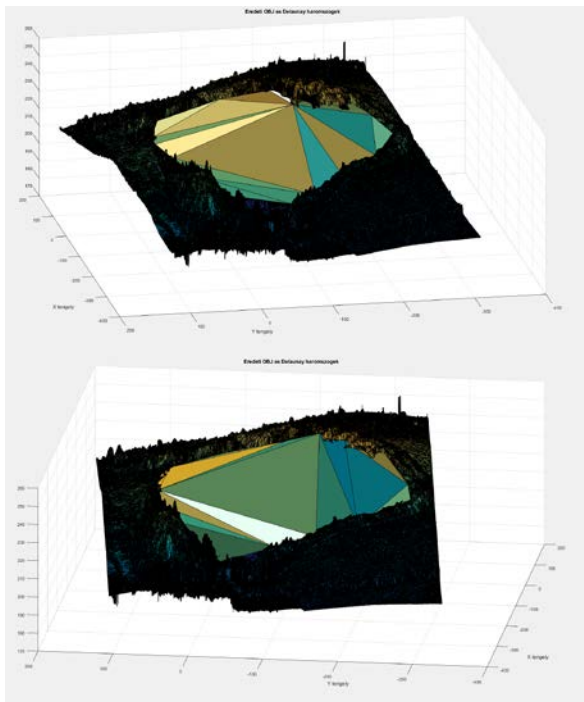


Fig. 10. Different Delaunay surfaces on the 3D model of active open pit mine

University,
<http://people.eecs.berkeley.edu/~jrs/papers/meshbook/>)

	Volume
Original mine model	~1.573.000 m ³
With covering surface	~1.591.000 m ³
With covering surface based on less reference points	~1.607.000 m ³
With covering surface based on less reference points	~1.598.000 m ³
Rotated covering surface based on less reference points	~1.583.000 m ³

Table 3. Volume of active open pit mine with different cover surfaces

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