ГЕОЛОГІЧНА ІНФОРМАТИКА

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USE OF B-SPLINES IN DEVELOPMENT OF AUTOMATED GEOLOGICAL-SURVEYING SUPPORTSYSTEM

(Рекомендовано членом редакційної колегії д-ром фіз.-мат. наук, проф. Б.П. Масловим)

***Purpose.** The effectiveness of the development of an information system for quarry management is primarily determined by the level of geological and surveying support (GSS), which includes solving such basic tasks as calculating reserves (operational and complete), accounting for ore mining, building the information base for mining planning and management, and field modeling, and career, ore body contouring, etc. The purpose of this work is to develop and use B-Splines in the automation of geological surveying software in the quarry.*

***Research methods.** The basis of many tasks is the construction of surfaces. For the first time in recent years, an uneven rational B-spline (NURBS) is used to describe them, which most fully satisfies the following criteria: the model's adequacy to the real representation, the efficiency of model formation and surface construction, and the visualization of the model in three-dimensional space.*

***Scientific novelty.** The advantages of constructing surfaces using NURBS are as follows: ease of calculation; sufficient smoothness; construction of the surface of any degree of complexity; using the weights of the control points, control of the surface (it can pass strictly through the specified control points). The latter property made it possible with the help of a NURBS surface to effectively model the day surface of a quarry with a strict passage of the surface through points of the ledges.*

***Practical significance.** For the joint Russian-Mongolian enterprise Erdenet (Mongolia), developing the copper-molybdenum deposit, an integrated automated GSS system has been developed and has been in operation for many years. Software and algorithmic tasks of the system are constantly being improved. This article presents its latest developments and development paths. The use of NURBS allowed us to construct the day surface of the open-pit mine, to improve the complete calculation of reserves, the accounting of ore mining, and the delineation of ore bodies along the open-pit horizons.*

***Results.** The software is implemented in C++ and C# for Windows. To build three-dimensional graphics, the tools of the open graphic library OpenGL are used. Separate modules of the developed GSS system were used at the Novokrivoyorogsk and Ingulets mining and processing plants. The methodology for constructing automated GSSs has been approved by many years of positive experience in industrial implementation and can be used for non-ferrous ore and iron ore deposits.*

***Keywords:** B-spline, NURBS surface, open pit surface modeling, ore body contouring, ore mining accounting.*

The problem and its connection with scientific and practical tasks.

In recent years, integrated mountain packages (GPI), which are being developed in non-CIS countries, have been widely developed. The GPI provides access to the most common database management systems (DBMS), has a modular structure and stores the results in accepted storage formats. This provides the possibility of subsequent use of the results by other applications. The information core of the GPI is a geological surveying system that solves a wide range of tasks, ranging from the initial processing of surveying surveys and well testing data to construct a DSM and ending with the calculation of reserves, the determination of optimal mine workings and the planning of mining operations. The leading companies in the world market offer the following most popular GPIs: Gemcom Surpac (in 2006, Gemcom completed the acquisition of Surpac Minex Group (*Company GEMCOM, 2006*)), Maptek, Mintec, CAE Mining (in 2010, CAE acquired Data-mine Group (*Trade Press Release, 2010*)) Techbase, IFM.

The Gemcom Surpac system was developed by Canadian company Gemcom Software International Inc. (*GEMCOM, 2008*) and includes various functions, ranging from the input of primary data to block modeling of fields, design and planning of open and underground mining.

The Australian company KJRA Systems, a member of the well-known MARTEK group of companies (*MAPTEK, 2012*), has developed and sells a powerful and rather expensive integrated system "Vulcan", which has a large set of modules for solving various problems in the field of geology, mining, mine surveying, and ecology.

CAE, after its acquisition in April 2010 of the Datamine Group, presents the CAE Mining product as advanced in the field of creating innovative technologies and services for planning, managing and optimizing mining operations (*TECHBASE, 2011*). The company operates in nine countries. CAE Mining offers advanced solutions ranging from the exploration and management of ore body modeling data to mining planning and operational management.

It is necessary to make a number of general comments regarding foreign integrated systems:

- the systems are designed to work with highly qualified specialists (surveyors, geologists, miners) who have undergone a long training cycle abroad or in consulting firms;
- the systems work effectively only on powerful personal computers or graphic workstations, the cost of which exceeds 25–50 thousand dollars;
- the cost of basic software is up to 25 thousand dollars, and the purchase of an additional set of modules can increase the cost of the package to 100–200 thousand dollars;
- many foreign packages have a complex, un-Russified and not very "friendly" user interface, which does not take into account the peculiarities of the working conditions in domestic practice.

Foreign packages are developed taking into account high versatility in order to maximize profits. No large firm will spend a long time adapting a software product at a specific mining enterprise. If for solving the problems of prospective development of a field development, in most cases, a universal approach can be used and services from design and research institutes can be abandoned, then additional development is required to solve many geological surveying tasks during field operation. Even the module for calculating reserves, which is one of the main ones in the GPI and which determines the cost and efficiency of the system core, cannot claim to be highly versatile.

Integrated automated GSS system has been developed and maintained for many years for the joint Russian-Mongolian enterprise Erdenet (Mongolia), which is developing a copper-molybdenum deposit. The software and algorithmization of the system tasks are constantly being improved. This article shows the latest developments and the ways of development. The scheme of the integrated system of GSSs is shown in fig. 1. Here are 8 main modules of the system.

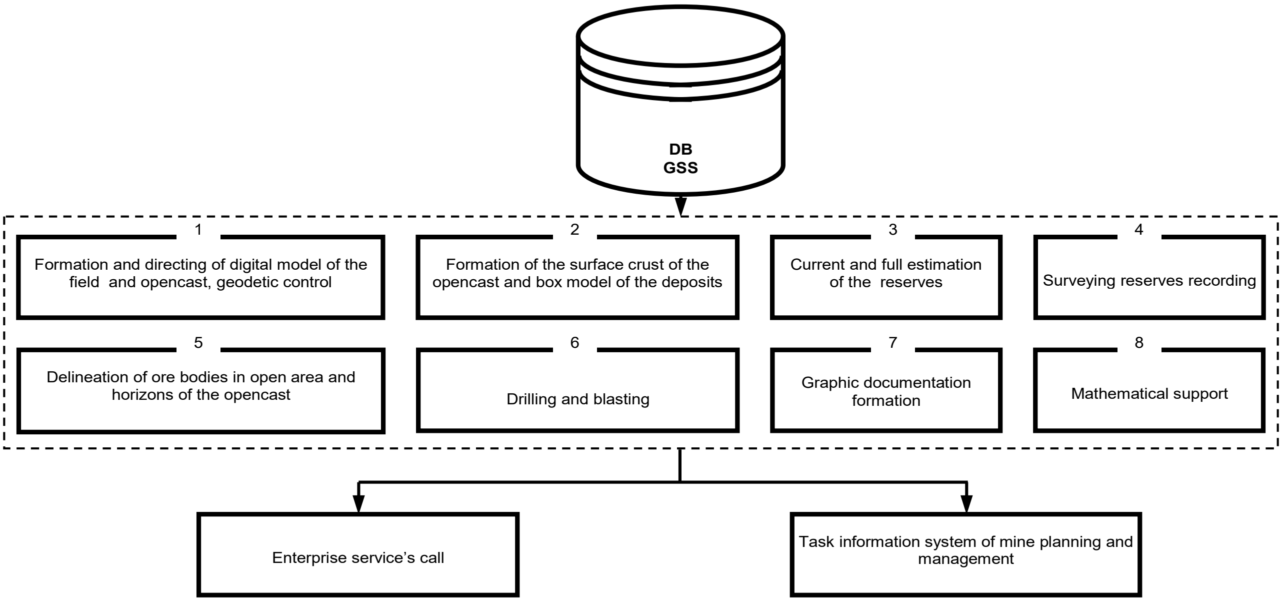

Fig. 1. Scheme of integrated geological surveying system

Studies and publication analysis.

The construction of surfaces is at the heart of many problems.

For the first time in recent years an uneven rational B-spline (NURBS) is used for their description, which most fully satisfies the following criteria:

- adequacy of the model to real representation;
- efficiency of model formation and surface construction;
- visualization of the model in three-dimensional space.

Its usage made it possible to construct a day surface of the opencast (module 2), to improve the full calculation of reserves (module 3), ore output accounting (module 4), and delineation of ore bodies in the horizon of the opencast (module 5).

Formulation of the problem.

Let us give an example of constructing an arbitrary NURBS surface, which, in general form, represents the dependence of $Z = f(X, Y)$. The values of Z can be the marks for constructing the day surface of the opencast; the sampling data for the wells in certain sections of the opencast, and so on.

First, a rectangle, which describes the area under investigation, is constructed. Next, an interpolation network is formed according to a certain index Z with the selected network step. The network step is selected in such a way as to evaluate the characteristic of the variability of the input data. The value of the indicator under study is determined in the nodes of the network. Various methods of interpolation (reciprocal distances, polynomial, criging point, etc.) are used, the simplest of which is the method of reciprocal distances:

$$Z_A = \frac{\sum_{i=1}^{N} Z_i \cdot d_i^{-\alpha}}{\sum_{i=1}^{N} d_i^{-\alpha}},$$

where Z_A – is the value of the indicator in the node A; N – is the number of nearest points; α – is the degree of interpolation; d_i – is the distance between the nearest point and the interpolation node; Z_i – is the value of the indicator at the point closest to the interpolation node.

Then, based on the data of the interpolation network, the nodes of which are breakpoints, a NURBS surface is constructed.

Material and results Presentation.

The result of the construction of B-spline curve based on 11 test points is shown in fig. 2. The order of the polynomial for the construction of the corresponding curve is chosen $m = 4$ (cubic polynomial).

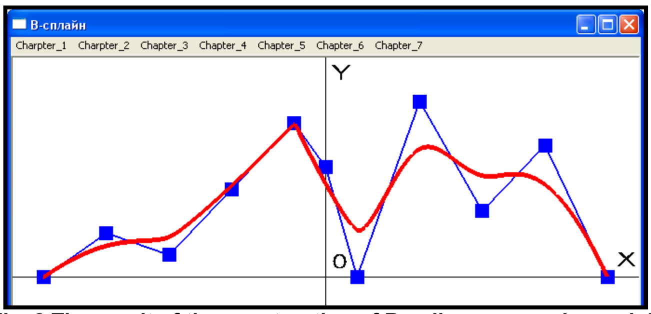

Fig. 2.The result of the construction of B-spline curve using weigh

Let's point out the main benefits of B-spline (*Роджерс и Адамс, 2001*):

1. Ease of calculation. Connecting function is evaluated in simple recursive manner. It is advisable to use the functions to connect a second or third degree.

2. Local control over the curve. Change in one control point does not affect the change in the curve, and is only in its particular area. This is due to the fact that only a small number of control points, depending on the degree of the polynomial, affect each connecting function.

3. Using weights to pass through strictly defined locations.

In fig. 3 we are showing the profile of the bench in open pit, described by B-spline, which has repeated the profile of the benches with high accuracy.

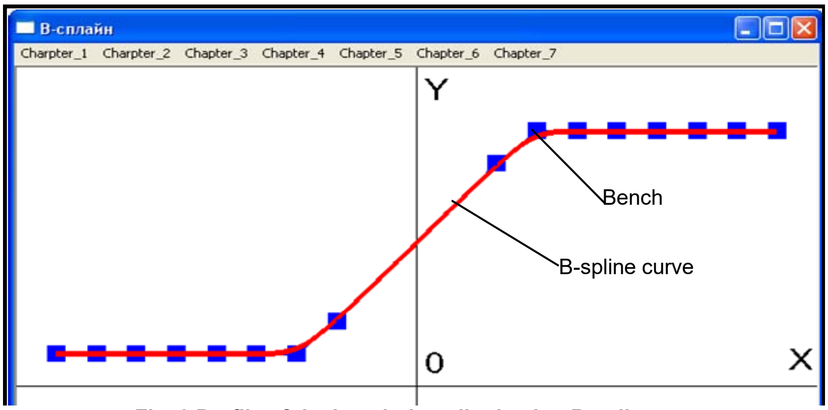

Fig. 3.Profile of the bench described using B-spline

When applying methods of constructing B-spline curves on NURBS-surface, the following formula is used (*Хилл, 2002*):

$$P(u,v) = \frac{\sum_{i=0}^{M}\sum_{k=0}^{L} w_{i,k} P_{i,k} N_{i,m}(u) N_{k,n}(v)}{\sum_{i=0}^{M}\sum_{k=0}^{L} w_{i,k} N_{i,m}(u) N_{k,n}(v)},$$

where $(M+1)$ – number of control points on the axis *OX* (numbered points from 0 to *M*); $(L+1)$ – number of control points on the axis *OY* (numbered points from 0 to *L*); $P_{i,k} = (x_{i,k}, y_{i,k}, z_{i,k})$ – the coordinates of the control points; $w_{i,k}$ – the weight coefficients of control points; $N_{i,m}(u)$ и$N_{k,n}(v)$ – correspondingly connecting B-spline functions in the direction of the axes *OX* and *OY*; *m* and *n*, respectively, are the orders of connecting B-spline functions $N_{i,m}(u)$ and $N_{k,n}(v)$; $u \in 0, \ldots, u_{max}$ (u_{max} – maximum value in the knot vector *u* in the direction of the axis *OX*, equal to $M - m + 2$); $v \in 0, \ldots, v_{max}$ (v_{max} – the maximum value of the knot vector *v* in the direction of the axis *OY*, equal to $L - n + 2$).

Let us consider the implementation and improvement of some modules of an automated geological surveying system based on the use of B-splines for constructing surfaces (modules 2, 3, 4, 5 in fig. 1).

Module 3 "Current and full estimation of the reserves" uses surface construction for the implementation of full estimation of reserves using the method of vertical sections (*Зеленский и др., 2010*).

The technique for realizing the full calculation of stocks by the method of vertical sections is as follows.

First, using the mathematical apparatus of B-splines, two surfaces of the opencast are constructed from the initial data of bench edge of the digital open cast models, respectively, at the beginning of the development and the design of the open-pit boundaries of the quarry.

The advantage of constructing the surface of the opencast is the availability, as the initial data, only of the *X, Y, Z* coordinates of the upper and lower bench marks, which are contained in the digital opencast model (DOCM) (fig. 4). Let us consider the technique of constructing the surface of the opencast using B-splines (*Зеленский и др., 2009*).

This is done in the following sequence. First, a rectangular area *ABCD* on the opencast plan is selected from the display screen, as it is shown in fig. 4. Then the rectangle is covered by an accurate regular grid with a given step (in our case, the network step is 10 m).

At the nodes of the network with the coordinates *X, Y*, the method of squares of the reciprocal distances determines the values of the *Z* marks with respect to the points of the bench edges.

$$z_{i,k} = \sum_{j=1}^{n} z_j r_j^{-2} \Big/ \sum_{i=1}^{n} r_j^{-2},$$

where z_j – is the level point, which is the closest to the node being determined; r_j – is the distance from the nearest point to the node; *n* – is the number of nearest points.

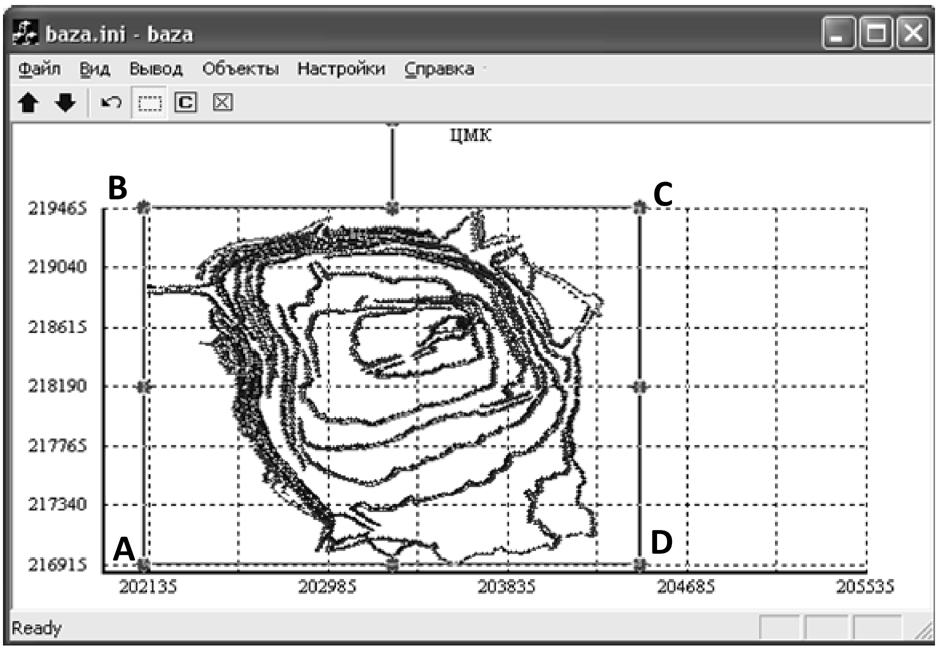

Fig. 4. To the formation of the surface of the opencast

In addition to the Z value, weighting coefficients are formed for the nodes of the network, and for the nodes closest to the level points (at a distance less than half the network step), the X, Y, Z coordinates are adjusted so that the point is shifted to the bench edge. In this case, the number of points in the direction of the OX axis and in the direction of the OY axis is conserved. It is necessary to set the weighting coefficients $w_{i,k}$ of node points in order to construct the NURBS surface using formula (1). All nodes of the network are assigned a weight equal to 1, except the nodes through which the edges of the bench edges go through. A significantly greater weight (a value of 1000 is assumed) is assigned to these nodes which ensures that the NURBS surface goes strictly through the points of the bench edge.

The result of obtaining the surface of the quarry is shown in fig. 5.

The surface of the project boundaries of the opencast is built in the same way.

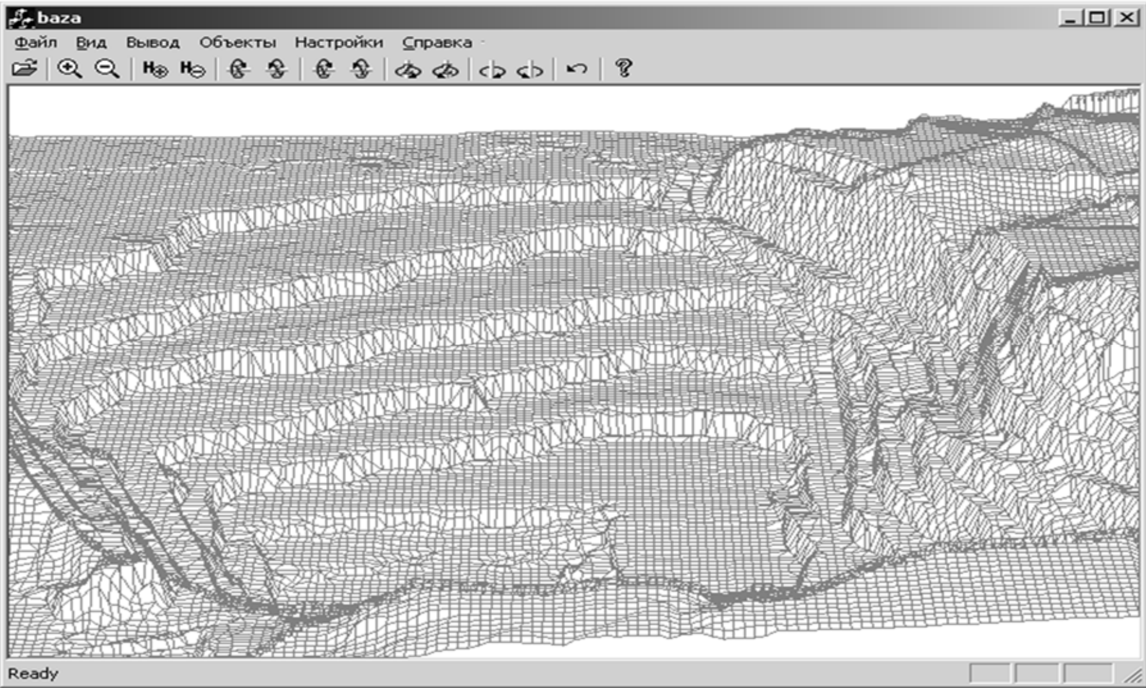

Fig. 5. Surface of the opencast constructed with B-splines

The ore outlines of vertical sections are determined in the next step. Each vertical section is limited from above by the line of intersection of the profile with the surface of the opencast at the beginning of the period, the lateral and lower line of intersection of the profile with the surface constructed along the design boundaries of the opencast.

As a result of the intersection of the profile with the surfaces of the opencast at the beginning of the development and the design boundaries of the opencast, we obtain an ore outline of vertical section.

Vertical sections are covered with an interpolation grid. In each node of the network, the type of ore and the qualitative indices for the nearest drill log of the long hole are estimated. Thus, the pit outline of the ore body is distinguished.

Knowing the area of the ore bodies and the distance between the vertical sections, the full calculation of the reserves is estimated.

In Module 4, "Surveying reserves recording" which is based on the B-spline opencast model, it is possible to perform a full calculation of the extracted rock mass for the reporting period (usually a month). On the daily surface of the opencast before and after mining, it is possible to estimate the total volume of the extracted rock mass as a whole in the opencast, and not only its individual sections.

Based on the model of the daily surface of the opencast, the volume of the extracted rock mass is determined with B-splines. The surface of an opencast in the form of a B-spline is represented by a set of "spatial" quadrilaterals, the coordinates of which, as a rule, are not in the same plane. In the same given rectangular area, which defines the pit limits, two opencast surfaces are constructed – at the beginning and end of the reporting period. In this case, the X and Y coordinates will be exactly the same for the two surfaces, and only the Z marks will differ.

Further, the volume of the extracted rock mass during the reporting period is calculated using the following formula

$$V = \sum_{i=1}^{n} (Z_i - Z_{le}) \cdot S_i - \sum_{j=1}^{n} (Z_j - Z_{le}) \cdot S_j$$

where n – is the number of "spatial" quadrilaterals, Z_i, Z_j– are the average elevations for the coordinates of the *i-th (j-th)* "spatial" quadrilateral of the surface, respectively, at the beginning and end of the reporting period, Z_{le} – is the lowest elevation of the opencast, S_i, S_j – are the areas *i-th (j-th)* – quadrangles respectively at the beginning and end of the reporting period.

The expression $(Z_i - Z_{le}) \cdot S_i$ in the formula is the volume of the rock mass in a separate elementary prism, the upper base of which is the "spatial" quadrilateral of the surface, and the lower one is its projection onto the horizontal plane.

In fig. 6, the advance of the mining front (the bench edge) during the reporting period is shown in dark colour.

On the basis of the digital model of the deposit, which contains the coordinates and quality indicators for blasting and exploratory wells strictly along the horizons of the opencast, it is possible to obtain qualitative indicators in these elementary prisms, which allows determining the content of the indices in the extracted rock mass.

The implementation of module 5 "Delineation of ore bodies in open area and horizons of the opencast" is carried out in the following sequence (*Зеленский и др., 2011; Зеленскийи, Лысенко, 2013*).

First, the planned horizon is selected with the data of the tested wells, on which the rectangular area to be examined is selected.

In fig. 7. the location of the wells and the data of their testing according to Cu_{ob}, is given, and in fig. 8 interpolated Cu_{ob}, values at nodes of a uniform network covering the rectangular area under investigation are also presented. Similarly, interpolated indices are formed for the second selected indices – Mo_{ob}. These indices are used to construct NURBS surfaces.

Fig. 9 shows the NURBS-surface according to the indicator Cu_{ob}, fig. 10 is its iso-content. Fig. 11 shows the delineation of the ore body by $Cu_{ob} \geq 0{,}4$ % and $Mo_{ob} \geq 0{,}02$ %, where the selected region satisfies simultaneously the established conditions of the two indicators.

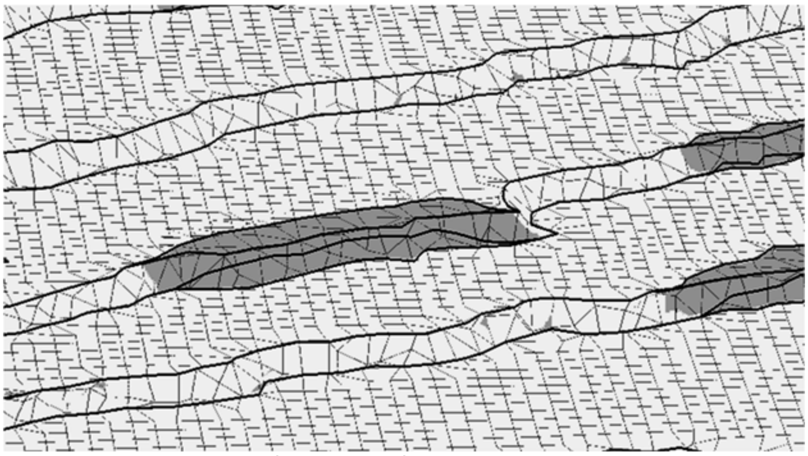

Fig. 6. Promotion of the mining front during the reporting period

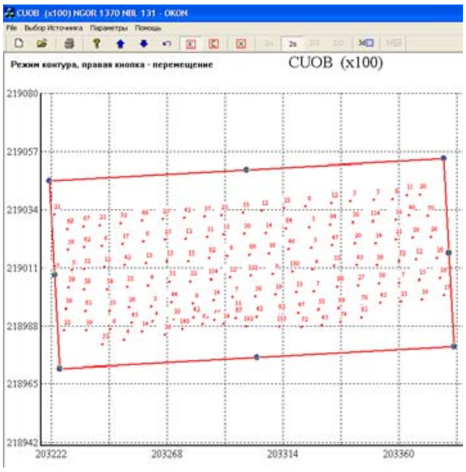

Fig. 7. Well location and their test data for *Cu_{ob}*

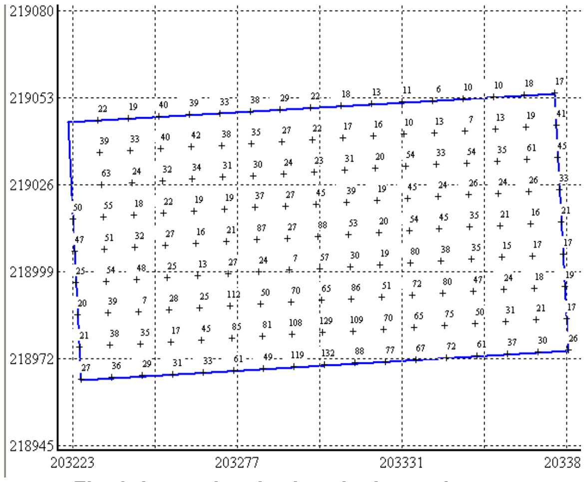

Fig. 8. Interpolated values in the study area

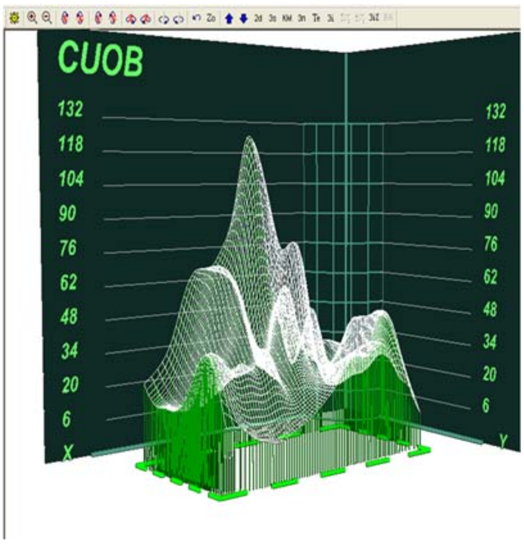

Fig. 9. NURBS – the surface according to Cu_{ob}

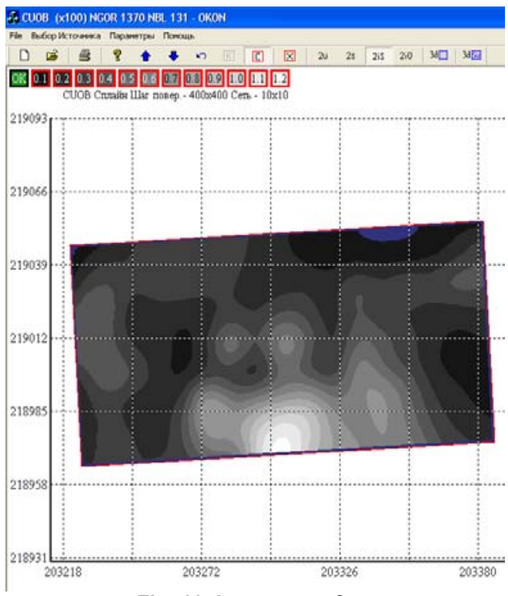

Fig. 10. Isocontent Cu_{ob}

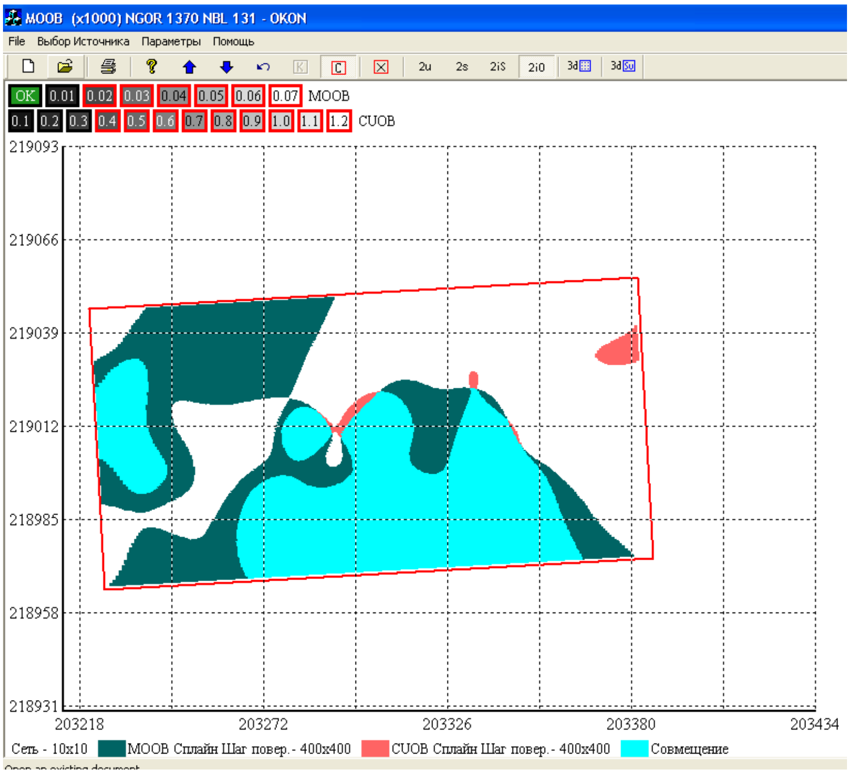

Fig. 11. To delineate ore bodies

The results of ore outline of ore bodies and selected varieties are used in the calculation of reserves and accounting for ore extraction. Decision results of ore outlining are stored in the database, which makes it easy to export them to external applications, for example, into the graphical environment of AutoCAD. Decision results of the solution are displayed on the display screen, printer and plotter.

As previously stated, the implementation of the algorithm for a controlled NURBS surface allows changing the nature of the passage of the surface according to spy points, changing the weight of their influence and shifting them within neighboring points. Such surface properties can be used to model "sharp" transitions between ore body and empty rock.

Conclusions and direction for future research.

The implementation of the software is in C++ and C# for Windows. To build a three-dimensional graphics, OpenGL's open graphics library tools are used. Separate modules of the developed system of GSSs were used at Novokrovyorzhsky and Ingulets Mining and Mineral Processing Plants.

The methodology of constructing of automated GSSs has been tested for many years having positive experience of industrial implementation and can be used for non-ferrous ore and iron ore deposits.

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ВИКОРИСТАННЯ В-СПЛАЙНІВ ПРИ РОЗРОБЦІ АВТОМАТИЗОВАНОЇ СИСТЕМИ ГЕОЛОГО-МАРКШЕЙДЕРСЬСКОГО ЗАБЕЗПЕЧЕННЯ

Мета. Ефективність розробки інформаційної системи управління кар'єром насамперед визначається рівнем геолого-маркшейдерського забезпечення (ГМЗ), яке включає вирішення таких основних завдань, як підрахунок запасів (оперативний і повний), облік видобутку руд, формування інформаційного базису для планування та управління гірничими роботами, моделювання родовища і кар'єру, оконтурювання рудних тіл тощо. Метою даної роботи є розробка і використання В-сплайнів у процесі автоматизації геолого-маркшейдерського забезпечення в кар'єрі.

Методи дослідження. В основі багатьох завдань використовується побудова поверхонь. Уперше в останні роки для їхнього опису застосовується нерівномірний раціональний В-сплайн (NURBS), який найбільш повно задовольняє такі критерії: адекватність моделі реальному уявленню, оперативність формування моделі й побудови поверхні, наочність відображення моделі в тривимірному просторі.

Наукова новизна. Переваги побудови поверхонь за допомогою NURBS полягають у такому: простота в обчисленні; достатня гладкість; побудова поверхні будь-якого ступеня складності; за допомогою вагових коефіцієнтів контрольних точок можна управляти поверхнею (вона може пройти строго через задані контрольні точки). Остання властивість дозволила за допомогою NURBS-поверхні ефективно моделювати денну поверхню кар'єру при строгому проходженні поверхні через точки бровок уступів.

Практична значимість. Для спільного російсько-монгольського підприємства "Ерденет" (Монголія), що розробляє мідно-молібденове родовище, розроблена і протягом багатьох років перебуває в експлуатації інтегрована автоматизована система ГМЗ. Програмне забезпечення та алгоритмізація задач системи постійно вдосконалюються. Наводяться останні її розробки і шляхи розвитку. Використання NURBS дозволило побудувати денну поверхню кар'єру, удосконалити повний підрахунок запасів, облік видобутку руд, оконтурювання рудних тіл по горизонтах кар'єру.

Результати. Реалізацію програмного забезпечення виконано на мовах С++ і С# для Windows. Для побудови тривимірної графіки використовуються інструментальні засоби відкритої графічної бібліотеки OpenGL. Окремі модулі розробленої системи ГМЗ використані на Новокриворізькому і Інгулецькому гірничо-збагачувальних комбінатах. Методологія побудови автоматизованого ГМЗ апробована багаторічним позитивним досвідом промислового впровадження і може бути використана для кольорових рудних і залізорудних родовищ.

Ключові слова: В-сплайн, NURBS-поверхня, моделювання поверхні кар'єру, оконтурювання рудних тіл, облік видобутку руд.

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ИСПОЛЬЗОВАНИЕ В-СПЛАЙНОВ ПРИ РАЗРАБОТКЕ АВТОМАТИЗИРОВАННОЙ СИСТЕМЫ ГЕОЛОГО-МАРКШЕЙДЕРСКОГО ОБЕСПЕЧЕНИЯ

Цель. Эффективность разработки информационной системы управления карьером прежде всего определяется уровнем геолого-маркшейдерского обеспечения (ГМО), которое включает решение таких основных задач, как подсчет запасов (оперативный и полный), учет добычи руд, формирование информационного базиса для планирования и управления горными работами, моделирование месторождения и карьера, оконтуривание рудных тел и т.д. Целью данной работы является разработка и использование В-сплайнов при автоматизации геолого-маркшейдерского обеспечения в карьере.

Методы исследования. В основе многих задач используется построение поверхностей. Впервые в последние годы для их описания используется неравномерный рациональный В-сплайн (NURBS), который наиболее полно удовлетворяет следующие критерии: адекватность модели реальному представлению, оперативность формирования модели и построения поверхности, наглядность отображения модели в трехмерном пространстве.

Научная новизна. Преимущества построения поверхностей с помощью NURBS состоят в следующем: простота в вычислении; достаточная гладкость; построение поверхности любой степени сложности; с помощью весовых коэффициентов контрольных точек можно управлять поверхностью (она может пройти строго через заданные контрольные точки). Последнее свойство позволило с помощью NURBS-поверхности эффективно моделировать дневную поверхность карьера при строгом прохождении поверхности через точки бровок уступов.

Практическая значимость. Для совместного российско-монгольского предприятия "Эрдэнэт" (Монголия), разрабатывающего медно-молибденовое месторождение, разработана и в течение многих лет находится в эксплуатации интегрированная автоматизированная система ГМО. Программное обеспечение и алгоритмизация задач системы постоянно совершенствуются. В данной статье приводятся последние её разработки и пути развития. Использование NURBS позволило построить дневную поверхность карьера, усовершенствовать полный подсчет запасов, учет добычи руд, оконтуривание рудных тел по горизонтам карьера.

Результаты. Реализация программного обеспечения выполнена на языках С++ и С# для Windows. Для построения трехмерной графики используются инструментальные средства открытой графической библиотеки OpenGL. Отдельные модули разработанной системы ГМО использованы на Новокриворожском и Ингулецком горно-обогатительных комбинатах. Методология построения автоматизированного ГМО апробирована многолетним положительным опытом промышленного внедрения и может быть использована для цветных рудных и железорудных месторождений.

Ключевые слова: В-сплайн, NURBS-поверхность, моделирование поверхности карьера, оконтуривание рудных тел, учет добычи руд.