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Application of geostatistical methods for reconstruction of lithological and mineralogical structure of uranium deposit by interpolating well data

During the development of uranium deposits that use in-situ leaching extraction method, mineralogical and lithological structure of sub terrain media remains unknown and is limited to the data along the wells. In order to optimize the development process, the scheme of geotechnological polygon should be positioned by taking into account lithological and mineralogical characteristics of the deposit. Given article describes results of modeling of lithological and mineralogical structure of uranium deposit by using inverse distance weighting and kriging methods, that are widely used in oil and gas industry. These algorithms are part of interpolation module of geotechnological simulator software that was developed and integrated to the Institute of High Technology (KazAtomProm, Kazakhstan) for the purpose of optimization of the processes of uranium deposits development and production. The results show that these two methods can be practically used in Kazakhstan's uranium industry and the comparison show that values of uranium concentration, permeability coefficient and lithological rock type provided by kriging algorithm are more reliable and closer as compared with other method when applied on the uranium deposit. The developed software that focuses on uranium deposits would eventually reduce costs of Kazakhstan's mines related to purchasing of costly CAD systems and drilling expensive exploration wells.
Key words: interpolation, geostatistics, inverse distance weighting, kriging, uranium, variogram.

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Ұңғы бойындағы мәліметтерді интерполяциялау арқылы, пласттағы минерологиялық пен литологиялық құрылымын қайта қалпына келтіру үшін, геостатистикалық әдістерді салыстыру

Уран кен орнын жер асты шаймалау әдісімен өндіру кезінде пласттың минералогиялық пен литологиялық құрылымы белгісіз және тек ұңғы бойындағы мәліметтермен шектелген. өңдеу процесін оңтайландыру үшін геотехнологиялық полигон схемасын орналастыру барысында минерал кен орнындағы литологиялық пен минералогиялық құрылымын ескеру керек. Берілген мақалада уран кен орнының құрылымын интерполяцииясы қашықтыққа кері өлшенген мен кригинг әдістерімен жасалып, нәтижелері салытсырылған. Осы екі әдіс мұнай мен газ индустриясында кең қолданылады. Кен орнын сипаттауға арналған есептеу алгоритмі уран кен орны жұмысын оңтайландырға негізделген геотехнологиялық симулятор модулі болып табылады. Нәтижесінде, сипатталған екі әдіс, уран индустриясында қолдануға болатындығын көрсетті. Осы екі әдіс нәтижелерін салыстыру кезінде уран концентрациясын, өткізгіштік коэффициенті мен литологиялық типтері сияқты таужыныстарының қасиеттерінің интерполяциясы кезінде кригинг әдісі аса сенімді және шындыққа жақын нәтижелер беретінін көрсетті. табылады.
Түйін сөздер: интерполяция, геостатистика, қашықтыққа кері өлшенген әдісі, кригинг, уран, вариограмма

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Сравнение геостатистических методов для восстановления литологической и минералогической структур пласта путем интерполяции скважинных данных

При разработке урановых месторождений методом подземного выщелачивания минералогическое и литологическое строение месторождений остается неизвестным и ограничено лишь данными на скважинах. Для оптимизации процесса разработки необходимо расположить схему геотехнологического полигона с учетом литологического и минералогического строений месторождений минералов. В данной статье приведены результаты моделирования литологического и минералогического строений урановых месторождения методами обратных взвешенных расстояний и кригинга, которые обширно применяются в нефтегазовой индустрии. Упомянутые алгоритмы расчета характеристик месторождений являются модулем разработанного авторами геотехнологического симулятора, служащего для оптимизации работы урановых месторождений. Результаты отображают, что данные методы могут быть применены к урановой индустрии, и в сравнении друг с другом, кригинг предоставляет более надежные и близкие к реальности результаты при интерполяции таких свойств породы как концентрация урана, коэффициент проницаемости и литологический тип породы.
Ключевые слова: интерполяция, геостатистика, метод обратных взвешенных расстояний, кригинг, уран, вариограмма.

1 Problem statement

1.1 Background

According to World Nuclear Association 12% of World's uranium resources can be attrubuted to Kazakhstan, which had produced as much as 22830 tonns of uranium by 2014. Since 2009 Kazakhstan has become an undisputable leader in uranium production. Almost 2/5 of planet's uranium was produced in Kazakhstan [3].

The in-situ leaching (ISL) is a leading method of uranium production in many countries, including USA and Kazakhstan. ISL requires injection of various solution into subterrain porous media in order to dissolve minerals containing uranium, followed by extraction with help of production wells [4].

The core of the problem lies in expensiveness of exploration procedures. So far, uranium exploration relies solely on well drilling, and on using different probes to determine uranium concentration in stratum. Due to the costliness of the drilling process and relatively far distances between wells, interpreting lithological data and uranium concentration between wells becomes a challenge [8]. Moreover, a hydrodynamical model of leaching solution flow in subterrain porous media would make it easier to monitor and optimize the production process, thereby reducing the expenses connected to uranium production. A simulation software that was developed under Kazakhstan government funding project which gives the ability to determine various geological and hydrodynamical properties and consists of the following modules:

1. geological modeling;
2. hydrodynamical modeling;
3. mass transfer module and
4. streamline module.

The construction of hydrodynamical model relies on existing hydrodynamical properties of subterrain environment. However, the exact (measured) data is only known at wells, therefore, geostatistical methods must be used in order to determine these properties in between wells. Hence, accuracy of hydrodynamical model is directly dependent on accuracy of geostatistical methods used in calculation. In the context of this article two known geostatistical methods were implemented: inverse distance weighting interpolation and kriging. While these two methods are extensively used in oil and gas industry, their application to uranium exploration and production should be studied.

1.2 Problem statement and research approach

The input data consists of lithological and hydrological information collected from 35 real uranium production wells located in rollfront deposit in Kazakhstan. Uranium leaching wells are usually positioned in a shape of hexagon with one production well located in the center and six injection wells around it [5] (Figure 1.2). The reliability of inverse distance weighting and kriging methods in the context of uranium resources will be estimated using following steps:

1. remove one well with its data;
2. interpolate data using respective method;
3. compare results with measured data

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35 wells used in estimation are shown in a (Figure 1.2). As an example, a well which is removed for reliability estimation is circled in red.

2 Existing calculation methods

Several geostatistical interpolation methods exists that can be used to interpret the data between the wells such as linear interpolation, inverse distance, kriging, Discrete Smooth Interpolation, Sequential Gaussian Simulation etc [1, 2].

Two of them were developed and applied to the problem: inverse weighting distance and kriging. Each of mentioned methods has its own specific characteristics that affect results and performance.

2.1 The inverse weighting distance method

The inverse weighting distance method is based on the assumption that nodes of the grid that are closer to the calculated node has more influence to the resulting value, rather than nodes that are further away. In order to calculate the value of the node by using this method, the following two parameters can be used to adjust the resulting value: the degree of influence and anisotropy, which defines the effect of the direction on the result (Figure 2.1) [1].

The general formula of inverse weighting distance method is as follows:

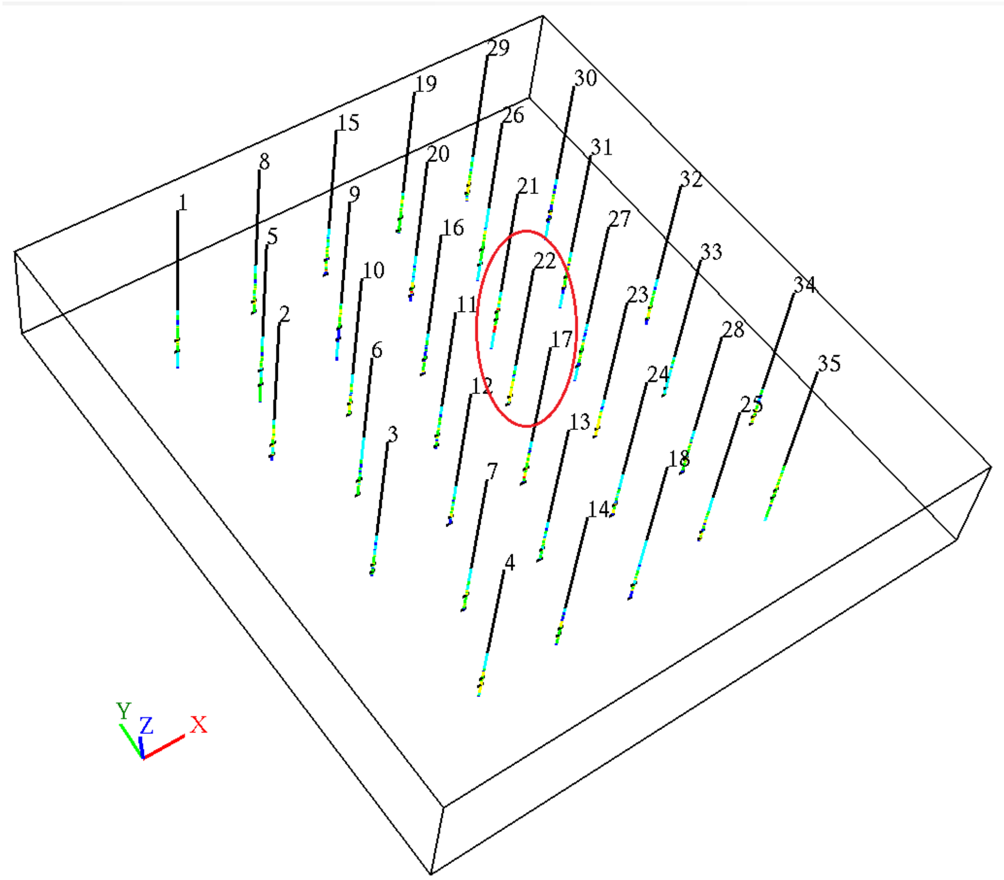

Figure 1–The calculation block covering 35 uranium production wells. The well number 22 is removed from input and used for result reliability estimation

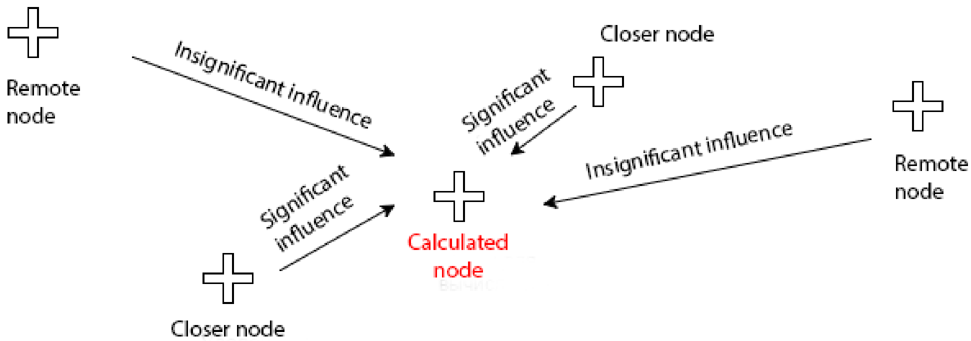

Figure 2–The impact of surrounding nodes on the calculated node

$$Z^*(x) = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} * Z(x_i)}{\sum_{i=1}^{n} \frac{1}{d_i^p}}, \tag{1}$$

where $Z^*(x)$ is the resulting value of the calculated node x, which is being interpolated; $Z(x_i)$ is the value at each node x_i; d_i is distance between nodes x and x_i; p is degree of influence of the node x_i at the value of the node x.

This method is also able to take into account the anisotropy of the media, which is calculated by the following formula:

$$d = \sqrt{a(x - x_i)^2 + b(y - y_i)^2 + c(z - z_i)^2}, \quad (2)$$

where a, b and c are the coefficients of anisotropy in each direction.

The advantages of the inverse weighting distance method lies in its simplicity and effective computational resource use. The method does not take into consideration any statistics regarding the distribution and shape of the values in media [1, 7].

2.2 Kriging interpolation

Kriging is one of more favored and effective methods of interpolation that is often used in interpretation of sub terrain data. In comparison to the inverse weighting distance, apart from anisotropy, kriging defines a mathematical model by which particular points have particular influence (the weight) on a calculated node. This model is called a variogram [2].

There is a whole family of kriging algorithms that can be applied depending on the specific characteristics of the case. In the scope of this article Ordinary Kriging was used which consists of the steps described in following paragraphs.

Firstly, a variogram must be defined by using the following formula:

$$\gamma(h) = \frac{1}{2}E(Z(x + h) - Z(x))^2, \quad (3)$$

where $\gamma(h)$ is a value of a variogram function for the distance between nodes equal to h, and a values $Z(x), Z(x + h)$ at the nodes x and $x + h$ respectively. Function E is describes arithmetical mean.

By choosing several distances h and by calculating the value of a variogram for all nodes located at that distance, it is possible to find an approximate model, that describes dependence of a variogram from the distance between nodes. The following three models are frequently used [2]:

1. Spherical model

$$\gamma(h) = \begin{cases} sill(\frac{3}{2}\frac{h}{2} - \frac{h^3}{2a^3}), & h \le a \\ sill & h > a \end{cases} \quad (4)$$

2. Exponential model

$$\gamma(h) = sill(1 - e^{-\frac{h}{a}}) \quad (5)$$

3. Gaussian model

$$\gamma(h) = sill(1 - e^{-\frac{h^2}{a^2}}) \quad (6)$$

In all cases described above *sill* becomes variogram's upper limit, a (also known as range) is a value along the axis h, after which the variogram ends its fluctuations. In other words, influence of nodes that are located at the distance further from a, is so insignificant, that it can be neglected. The value of *sill* can be manually picked up, or determined by the following formula:

$$sill = \sigma_x = E(x - E(x))^2, \tag{7}$$

where σ_x is variance.

As an alternative the function of variogram can be substituted by a function of a co-variogram:

$$C(h) = C(0) - \gamma(h); C(0) = \sigma_x = sill. \tag{8}$$

Secondly, weights must be calculated for each node. In the process of measuring value for the unknown node the weight of influence λ_i must be calculated for each other known node by solving this matrix equation:

$$\begin{bmatrix} C(x_1 - x_1) & C(x_1 - x_2) & \dots & C(x_1 - x_n) & 1 \\ C(x_2 - x_1) & C(x_2 - x_2) & \dots & C(x_2 - x_n) & 1 \\ \dots & \dots & \dots & \dots & 1 \\ C(x_n - x_1) & C(x_n - x_2) & \dots & C(x_n - x_n) & 1 \\ 1 & 1 & \dots & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} C(x - x_1) \\ C(x - x_2) \\ \dots \\ C(x - x_n) \\ 1 \end{bmatrix} \tag{9}$$

Lastly, the value at the node must be calculated. After all weights were successfully calculated the value at the node x is determined by the formula below:

$$Z^*(x) = \sum_{i=1}^{n} \lambda_i Z(x_i), \tag{10}$$

where the condition $\sum_{i=1}^{n} \lambda_i = 1$ is mandatory.

In comparison to other interpolation methods, kriging results a has lesser deviation from the from the actual value [6, 2, 7].

3 Results evaluation

Figure 3 illustrates the results that were achieved by implementing the aforementioned method (well with data removal). Charts include results acquired from kriging and inverse distance methods. Results were collected for both filtration coefficient and uranium concentration (left and right charts respectively). On both charts results of both interpolation methods can be compared with real data measured with appropriate equipment. Chart on the left shows filtration coefficient by well height, whereas chart on the right illustrates uranium concentration on the same well.

According to International Atomic Energy Agency rollfront uranium deposits that a prevalent in Kazakhstan are defined as “zones of uranium-matrix impregnations that crosscut sandstone bedding and extend vertically between overlying and underlying less-permeable horizons” [9]. Expectedly, filtration coefficient would be minimal close to the top and bottom impermeable bedding, which is evident on Figure 3. Starting from around 253 meters depth to 277 meters depth the results start to diverge. At the beginning, Inverse distance method in particular, gives higher discrepancy from measured data rather that Kriging method. While being smooth it was unable to predict spikes in filtration coefficient. Around heights 260 and 270 Kriging provided relatively comparable spikes. For filtration coefficient, total estimation error of Kriging was less than of Inverse Distance with values equal to 85.2 and 93.3 respectively.

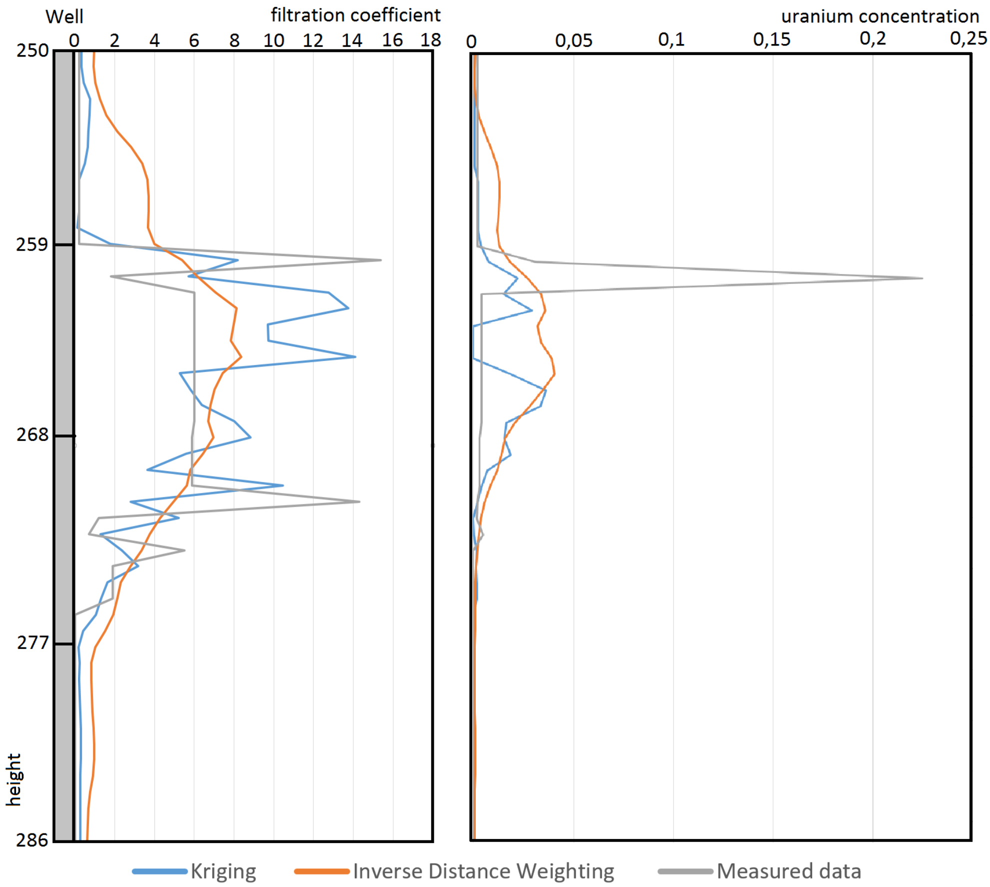

Figure 3–The calculation block covering 35 uranium production wells. The well number 22 is removed from input and used for result reliability estimation

For uranium concentration estimation both methods were proven as unreliable which can clearly be seen on the right chart of Figure 3. Both Kriging and Inverse Distance methods were unable to predict the abnormal rises and dips in uranium at wells. The total estimation error of Kriging was again lower that of Inverse distance with values equal to 0.42 and 0.61 respectively.

4 Conclusion

Overall Kriging provided slightly more reliable results than Inverse Distance. In general, filtration coefficient results did not have high deviation from measured data. It is clear, however, that the data provided to Kriging is insufficient for relatively precise uranium concentration estimation. Chemical, geological and hydrodynamical parameters should be used in interpolation in order for Kriging or any other method to produce reliable results.

While interpolation methods used for uranium deposits can be improved the technique of removal of input data from one well can be reused in future. This technique gives ability to test various methods for their reliability, and provides opportunity to compare them with each other. This work was accomplished within the "The development of information technologies to improve the efficiency oil, gas and uranium production"project under financial support from Ministry of Education of Republic of Kazakhstan.

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