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APPLICATION OF GEOSTATISTICS TO EVALUATION OF PENETROMETRIC MEASUREMENTS

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Abstract

Evaluation of changes to soil condition, e.g. in assessment of soil protection technologies in maize growing can be done through penetrometric measurements. Frequency of penetration measurements and their results in the form of graphical developments of penetration resistance do not offer a sufficient picture of complicated spatial configuration of soil particles. Application of non-traditional evaluation methods using variograms and special procedures of geostatistics make it possible to express more graphically differences between measured points in the chosen area. A suitable graphical program is able to express graphically and continuously the complexities of changes in soil condition and compare different tillage technologies. For assessing the suitability of geostatistics, the results of penetration measurements made in fields with different tillage technologies (no ploughing, minimum ploughing and ploughing) at the flowering stage of maize were used for the experiment. During measuring the penetration resistance, samples of soil in the experimental fields were withdrawn to determine soil volume weight and moisture. Based on the statistical processing of penetration measurements, graphical interpretations of the profiles of measured soil sections for individual tillage technologies up to a depth of 0.4 m were prepared using the linear variogram model under a Surfer program. In comparison with classic penetrograms, graphical profiles of individual technologies indicate significant differences in the soil condition.

WYKORZYSTANIE METOD GEOSTATYSTYCZNYCH W POMIARACH PENETRACYJNYCH GLEBY

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Słowa kluczowe: ocena technologii obróbki gleby, pomiary penetracyjne, metody geostatystyczne, program Surfer.

Streszczenie

Badania zmian stanu gleby, np. przy ocenie gleboochronnych technologii uprawy kukurydzy, można realizować za pomocą pomiarów penetracyjnych. Przedstawianie wyników pomiarów penetracyjnych w formie graficznego przebiegu oporu nie daje w pełni jasnego obrazu o złożonej przestrzennej strukturze gleby. Zastosowanie specjalnych metod oceny wyników pomiarów za pomocą krzywych wariacyjnych i odpowiednich metod geostatystycznych pozwala na bardziej dokładne określenie różnic między badanymi stanowiskami pola. Odpowiedni program graficzny pozwala w sposób poglądowy i spójny wyjaśnić złożone zmiany stanu gleby, umożliwiając porównanie różnych technologii jej obróbki. Przy ocenie przydatności metod geostatystycznych wykorzystano wyniki pomiarów penetracyjnych na polach z kukurydzą uprawianą w technologii bezorkowej, z minimalną i orkową obróbką gleby. Pomiary penetracyjne przeprowadzono w fazie kwitnienia kukurydzy, pobierając próbki gleby do określenia jej masy objętościowej i wilgotności. Na podstawie obróbki statystycznej wyników pomiarów penetracyjnych dla liniowego modelu krzywych wariacyjnych opracowano, za pomocą programu Surfer, graficzne interpretacje profili w przyjętych odcinkach do głębokości 0,4 m. Uzyskane „penetogramy" dotyczące poszczególnych technologii, w porównaniu z klasycznymi „penetogramami", wskazały na wyraźne różnice w stanie profilu glebowego, z dobrze widocznymi miejscami zwiększonego oporu penetracyjnego.

List of symbols

h	–	vector, known as distance,
$m(h)$	–	number of pairs of samples separated by distance h,
m x n	–	rectangular grid of dimensions,
p and q	–	distances in two different directions,
N	–	number of samples,
s^2	–	dispersion,
x	–	set of spatial 1, 2 or 3 dimensional co-ordinates,
$z(x_i)$	–	values in the locations x_i,
$\overline{z}$	–	average value of two pairs of samples,
g	–	semivariance.

Introduction and aim of the paper

Visual evaluation of the processed penetrograms obtained by penetrometric measurements requires a good ability to orient in the diagram and have some experience in their analysis. Penetrograms, however, are not suitable for an exact assessment of the course of penetration resistance in certain spatial arrangement. By studying different evaluation procedures we tried to find an optimum way of graphical interpretation on a measuring plane that is created by a set of measurements in vertical pushing the penetrometer into soil. This way of graphical representation is possible through isolines of penetration resistance, the exact position of which can be expressed by the use of complicated mathematical operations in the form of a topographic map. For representation of the isolines of penetration resistance it is suitable to use geostatistics methods and related programs, using these procedures.

Within the deposit geology a known method is used for evaluation of the variability in the contents of chemical elements, or other geological elements (e.g. coal bed thickness). This method was introduced by geologist Krige of South Africa, who dealt with the variability of gold content in the known deposits situated in Wittwaters-rand area (SAR). Based on his results published at the end of the 1950s, this method continued to be developed by French mathematicians and geologists leaded by Matheron. They found that the values of the content of elements or those of the content of another quantity which are a continuously changing variable in space can be considered to be a function of "position co-ordinates in one- through three-dimensional space". French Matheron´s statistical school, which started being denoted geostatistical school, has adopted the conception of "regionalized variable" to express a continuously changing variable in geological space, which cannot be described by any particular function. In theoretical descriptions of the regionalized variable its dependence on localization and connection with geometry and sample orientation is mentioned. Although its value varies continuously, sometimes it is done very fast and, above all, with different variability in various directions. According to Matheron, in the case of the regionalized variable it is the question of the realization of a random function in space.

The main means of research on variability in the regionalized variable is research on dispersion variance of the variable under study as a function of mutual distances of single measurement points. There is a correlation between values of the variable for single points terminating after some distance, and single measurement points can be considered to be mutually independent. This means is termed the variogram, which is used as a basis for other computations termed kriging. In principal, these are methods of a weighted average whose objective is an optimal estimation of an average value of the regionalized variable in given location or space. Weight is calculated by means of values derived from the variogram, which can be expressed as a function with different development. According to its development, we can talk about linear, quadratic, logarithmic or other models of the variogram. Different kriging methods are then based on these models. For this study, a linear model was chosen.

A principle of the method we used for our purpose is the representation of the cross section of soil horizon with marked points of a constant penetration resistance connected by means of lines, thereby forming a fictive area where different values of pressed soil are designated.

Theoretical foundations

According to McBratney and Webster (1986), theoretical principles of geostatistics can also be useful in the area of soil. Let us consider the soil property z, e.g clay content or electrical conductivity, which can continuously change in geographical space. The property given by the values $z(x_i)$ in the locations x_i, i = 1, 2,......., where x is a set of spatial 1, 2 or 3 dimensional co-ordinates. If we consider the values z in two locations, x and $x+h$, where h is the vector, known as distance, expressing their separation with distance and direction. Then dispersion (in this case we shall use the conception of variance) can be given

$$s^2 = \{z(x) - \bar{z}\}^2 - \{z(x+h) - \bar{z}\}^2$$

or

$$s^2 = \frac{1}{2}\{z(x) - z(x+h)\}^2 \qquad (1)$$

where is the average value of two pairs of samples.

The value s^2 is specific to x and $x+h$, and creates more possibilities of measurement use, soil being considered to be the realization of a random process with certain stationary conditions. These conditions are as follows:

1) the expected difference between values at two given points separated by distance h is 0:

$$E[z(x) - z(x+h)] = 0 \qquad (2)$$

2) the variance of differences in values depends on h and not on x, it is given by the relation:

$$\mathrm{var}[z(x) - z(x+h)] = E\left[\{z(x) - z(x+h)\}^2\right] = 2\gamma(h) \qquad (3)$$

These two conditions generate the so-called own hypothesis of the environment of the theory of regionalized variable. Based on the experiences reported by several sources, it is supposed to be widely used in the area of soil investigation as well.

Within the theory of regionalized variable, the quantity g is known as semivariance and it is estimation of s^2, the variance in location where samples consist of pairs. Semivariogram is then the representation of γ as dependent on h. Where the hypothesis of "environment" is valid, it contains every information of spatial variance of the soil property under study.

The hypothesis of "environment" also enables semivariances to estimate the simple realization of the process direct from the sample as:

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} \{z(x_i) - z(x_i + h)\}^2 \qquad (4)$$

where $m(h)$ is the number of pairs of samples separated by distance h. By arranging this set we can prepare the model semivariogram. Based on this method, another processing of regionalized variables can be performed until a shape of 2-dimensional semivariogram is reached. We can always use the general relationship to assess semivariances in discrete values h using equation (4). The assessment is objective. So for samples N at defined intervals along cross-section it can be written:

$$\gamma(h) = \frac{1}{2(N-h)} \sum_{i=1}^{n-h} \{z(i) - z(i+h)\}^2 \tag{5}$$

where now h is the integral number of sampling intervals. For a rectangular grid of dimensions m x n in the 2-dimensional semivariogram, two dimensions of its own with estimation are given as:

$$\gamma(p,q) = \frac{1}{2(m-p)(n-q)} \sum_{i=1}^{m-p} \sum_{j=1}^{n-q} \{z(i,j) - z(i+p, j+q)\}^2$$

$$\gamma(p,-q) = \frac{1}{2(m-p)(n-q)} \sum_{i=1}^{m-p} \sum_{j=1}^{n-q} \{z(i,j) - z(i+p, j-q)\}^2 \tag{6}$$

where p and q are distances in two different directions. Equation (6) gives a value for the right half of semivariogram. The function is symmetrical against the middle and thus, the second half can be determined by simple half turning. In the 2-dimensional representation it is usual that the development of the area of interest is not regular. Lengths of lines and columns are not the same then. The calculation is made through available data, designations must be adjust by relevant numbers of pairs during calculation.

Measuring conditions and penetrogram processing

Penetration measurements were carried out in the maize growing area, at Agrocontract Mikuláš in the south of Slovakia. Three tillage treatments (no ploughing, minimum (disk) ploughing and ploughing) were compared in the trial. Measurements were made in early maize varieties at the flowering stage. At the same time non-deformed soil samples were collected using a sampling device of our own construction and analysed for volume weight and instantaneous moisture of soil. Penetration resistance was measured by a penetrometer P-BDH 3A as described by BAJLA and HRUBÝ (1997), with a cone of dimensions according to ASAE S 313.2. Measurements were performed across rows, with approximately the same intervals of punctures. Out of plenty of measurements we have chosen some to demonstrate how to process the results obtained.

When the penetrograms processed are visually evaluated, it is necessary to orient in a right way in a diagram and have some experience in reading them. After primary processing penetrograms by statistical methods, we shall obtain sets of measurements characterizing the values of resistance for relevant positions and depths in the table form. The penetrograms processed for individual measurements are shown in Figure1.

Using program packages, it is possible to make the drawing of "isolines" development more accurate and faster. Among such program packages is a product by SAS Institute, Inc. For our study we used a Surfer software, part of the known product Golden. Surfer is the graphical software intended for designing contour maps and block diagrams derived from these maps. It is a set of several independent sub-programs, which are logically linked. It is designed mainly for making contour maps based on a non-regular grid of measurements. The Surfer program can process a set of 14,000 measurements maximum. The most intricate and time-most consuming part of the whole program is a subprogram Grid making it possible to convert measured data from the non-regular grid into the regular one, both rectangular and square. This process is often termed griding: databases can be stored in binary or ASCII forms, both systems can be selected. Next step is mathematical processing by the use of variograms. There is a correlation between values of the variable for single points, which terminates after some distance and individual measurements can be considered mutually independent. Then calculations termed kriging are used based on the variogram. In principle, these are methods of a weighted average the goal of which is to optimally determine an average value of the regionalized variable for given area or space. Weight is calculated by the use of values estimated from the variogram, which can be expressed as a linear or quadratic or logarithmic or other models. Various methdos of kriging proceed from these models. For our case study we used a linear model. The graphical representation of method like this is illustrated in Figure 2.

Discussion

After data processing and visualisation in the graphical form using penetrograms, it is possible to transform the data processed into the form characterizing the development courses of resistance isolines and/or other dependences. This transformation is suitable for more demanding experiments, when greater statistical sets are at disposal and exact calculations are required.

The methods of geostatistics were already used to process results from measuring soil characteristics in the 1980s, but only at present their application is more appreciated. Reasons are very prosaic. The method is quite demanding as far as managing the physical basis of processing data is concerned and evaluation is difficult. Nowadays fast computer systems with suitable programs, often arranged by segment, help to manage it.

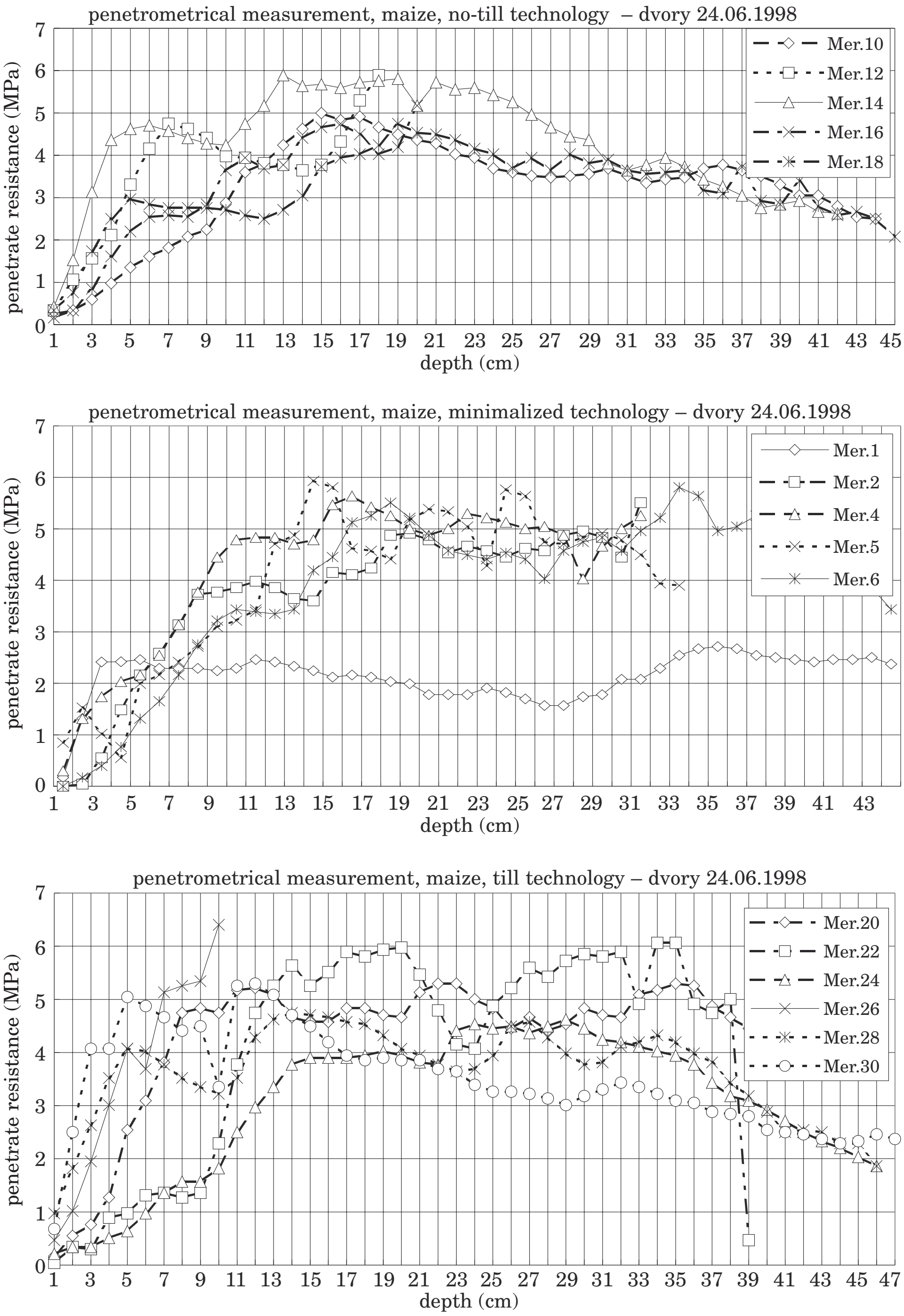

Fig. 1. The penetrograms processed for individual measurements

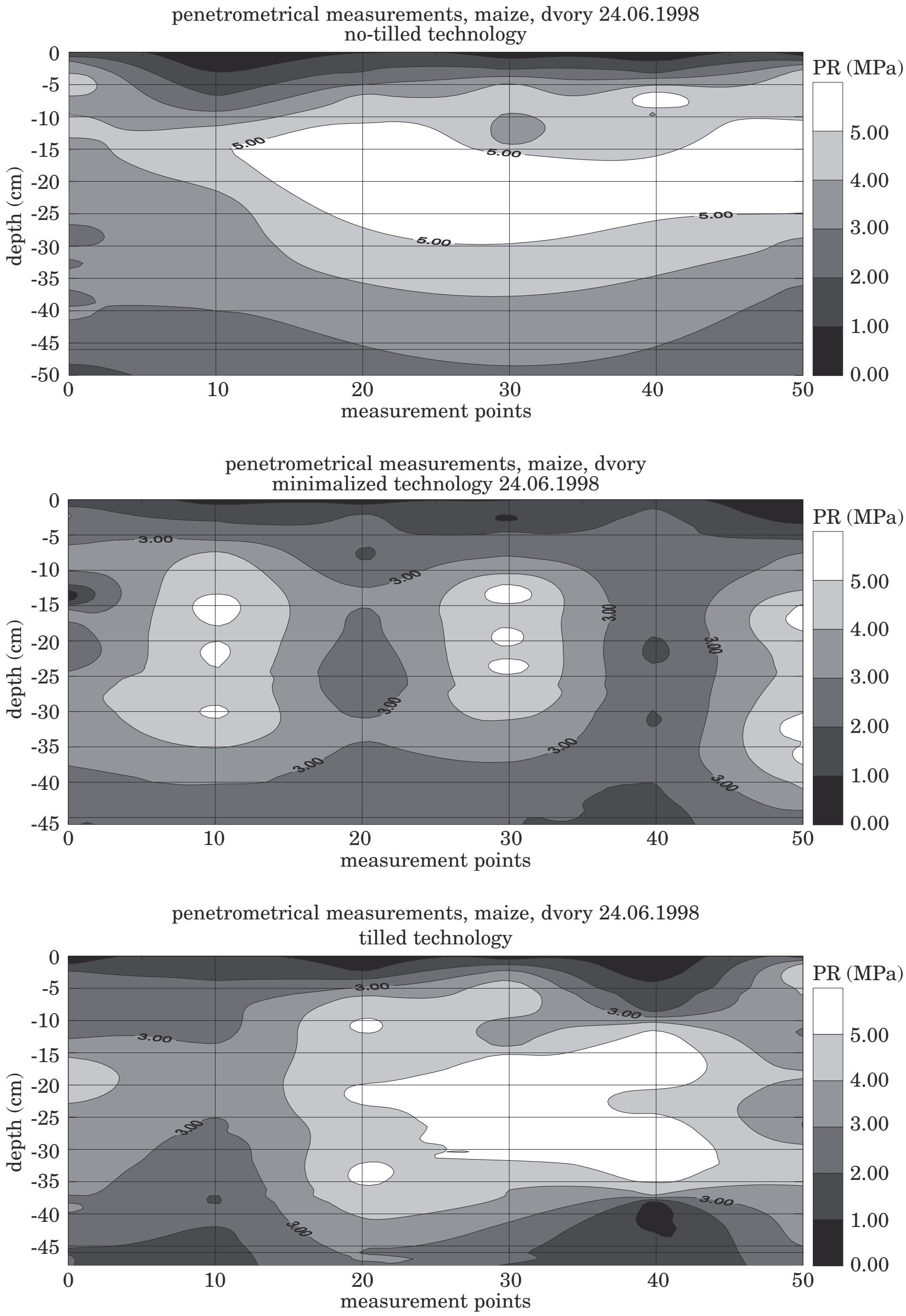

Fig. 2. The graphical representation of kriging method

One of the first who applied this method to a study on soil characteristics were VIEIRA et al. (1981), who explored the problems of an infiltration speed in terms of spatial variability. He has proved that the method can be utilized for assessment of field-measured values, but a sufficient number of measurements of the parameter under study is required. Among others were GAJEM, WARRICK and MYERS (1981), who tried to apply these methods to determination of spatial dependence of other soil parameters, pointing out the need of a suitable scale for soil analysis. MCBRATNEY and WEBSTER (1986) made an extensive analysis for the needs of estimation of soil properties. They paid attention to searching for functions of variograms, worked up the evaluating criteria of semivariograms and created some variance models. CHANG, SOMMERFELDT and ENTZ (1988) used this knowledge for salt content analysis of irrigated soils. Following this work, ENTZ and CHANG (1991) have elaborated a method for sampling of the area observed for the purposes of geostatistical analysis, and verified it when studying soil density. Analysis of soil aggregates was another sphere where geostatistical methods were used. CASTRIGNANO and STELLUTI (1999) applied geostatistical methods in combination with fractal geometry. The results were implemented in the form of a map. Based on correlation analysis, they confirmed suitability of these methods for soil characteristics study in terms of of spatial variability of the property under study.

Summimg up

When studying the instantaneous soil condition, it is very difficult to characterize the parameters representing soil deformation. In addition to selection of a measuring method, the right evaluation of parameters and primarily the interpretation of measurement results are important. Mean values of a certain number of measurements of a soil property calculated without giving a depth interval, i.e. for arable land, are simple to evaluate but do not bring any information on changes in vertical arrangement of the soil property investigated. Where the soil property can be measured with an expected spatial result, e.g. in measuring penetration resistance of cone, profile diagrams can depict, for instance, the results of changes to soil condition before and after a vehicle passage. In these analyses it is necessary to use suitable methods for determination of the consequences of these effects on soil, the dynamics of soil changes and their interpretation in such a way that the knowledge obtained is not only accurate enough and reliable, but also brings graphical and practical expression of complicated processes with a possibility of percieving the dynamics of these changes. The topographic representation of penetration resistance by means of isolines, with a presupposition of application of computer- aided geostatistical methods, can be method like this. The kriging algorithm used finds its application mainly in the area where the existence of certain space-oriented variability of the variable observed can be supposed. The advantages of kriging method will be appreciated in the field with a thin grid of measurements or in extrapolation on the edges of the areas under investigation. A certain problem is limitation of the field where an error of interpolation increases above an acceptable degree. In the method applied only a substantially restricted procedure is used to solve this variant. Kriging is the most suitable method for the interpolation of geological data, and it is therefore very useful for evaluating soil condition in using penetrometric methods. Some of program packages aiming at statistical and/or geostatistical methods can offer a convenient use of the method of kriging.

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