Standard Guide for Selection of Kriging Methods in Geostatistical Site Investigations[1]

This standard is issued under the fixed designation D5923; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Geostatistics is a framework for data analysis, estimation, and simulation in media whose measurable attributes show erratic spatial variability yet also possess a degree of spatial continuity imparted by the natural and anthropogenic processes operating therein. The soil, rock, and contained fluids encountered in environmental or geotechnical site investigations present such features, and their sampled attributes are therefore amenable to geostatistical treatment. Kriging methods are geostatistical techniques for spatial estimation belonging to the class of least-squares estimators. This guide reviews criteria for selecting a kriging method, offering direction based on a consensus of views without recommending a standard practice to follow in all cases.

1. Scope

1.1 This guide covers recommendations for selecting appropriate kriging methods based on study objectives, exploratory data analysis, and analysis of spatial variation.

1.2 This guide considers commonly used forms of kriging, including ordinary kriging, simple kriging, lognormal kriging, universal kriging, and indicator kriging. Multivariate, space-time, and other less-frequently used kriging methods are not discussed; however, this is not intended to reflect any judgement as to the validity of these methods.

1.3 This guide describes conditions for which kriging methods are not appropriate and for which geostatistical simulations approaches should be used.

1.4 This guide does not discuss non-geostatistical alternatives to kriging, such as splines or inverse-distance techniques.

1.5 This guide does not discuss the basic principles of kriging. Introductions to geostatistics and kriging may be found in numerous texts including Refs (**1-3**).[2] A review of kriging methods is given in Ref. (**4**).

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids
D5549 Guide for The Contents of Geostatistical Site Investigation Report (Withdrawn 2002)[4]
D5922 Guide for Analysis of Spatial Variation in Geostatistical Site Investigations
D5924 Guide for Selection of Simulation Approaches in Geostatistical Site Investigations

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

Current edition approved May 1, 2010. Published September 2010. Originally approved in 1996. Last previous edition approved in 2004 as D5923 – 96 (2004). DOI: 10.1520/D5923-96R10.

[2] The boldface numbers in parentheses refer to a list of references at the end of the text.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *additivity, n*—a mathematical property of a regionalized variable stating that it can be combined linearly in order to define a similar variable on a larger support.

3.1.2 *block kriging, n*—a form of kriging in which the variable to be estimated has a rectangular or possibly irregular one-, two-, or three-dimensional support.

3.1.3 *drift, n—in geostatistics*, a systematic spatial variation of the local mean of a variable, usually expressed as a polynomial function of location coordinates.

3.1.4 *estimation, n*—a procedure by which the value of a variable at an unsampled location is predicted using a weighted average of sample values from the neighborhood of that location.

3.1.5 *field, n—in geostatistics*, the region of one-, two- or three-dimensional space within which a regionalized variable is defined.

3.1.6 *indicator kriging, n*—a form of kriging in which all data are indicator variables.

3.1.7 *indicator variable, n*—a regionalized variable that can have only two possible values, 0 or 1.

3.1.8 *kriging, n*—an estimation method where sample weights are obtained using a linear least-squares optimization procedure based on a mathematical model of spatial variability and where the unknown variable and the available sample values may have a point or block support.

3.1.9 *kriging variance, n*—the expected value of the squared difference between the true value of an unknown variable and its kriging estimate, sometimes used as a measure of kriging precision.

3.1.10 *lognormal kriging, n*—the kriging of log-transformed variables followed by a back-transformation procedure based on a lognormal distribution model.

3.1.11 *nugget effect, n*—the component of spatial variance unresolved by the sample spacing, including the variance due to measurement error.

3.1.12 *ordinary kriging, n*—a form of kriging for which the mean of the estimated variable is an unknown constant and the sample weights sum to one.

3.1.13 *point, n—in geostatistics*, the location in the field at which a regionalized variable is defined. It also commonly refers to the support of sample-scale variables.

3.1.14 *point kriging, n*—a form of kriging in which the variable to be estimated has the same support as the sample data.

3.1.15 *regionalized variable, n*—a measured quantity or a numerical attribute characterizing a spatially variable phenomenon at a location in the field.

3.1.16 *search neighborhood, n*—the region within which samples are considered for inclusion in the kriging estimation process.

3.1.17 *simple kriging, n*—a form of kriging for which the mean of the estimated variable is a known constant and the sum of sample weights is unconstrained.

3.1.18 *simulation, n—in geostatistics*, a Monte-Carlo procedure for generating realizations of fields based on the random function model chosen to represent a regionalized variable. In addition to honoring a random function model, the realizations may also be constrained to honor data values observed at sampled locations.

3.1.19 *smoothing effect, n—in geostatistics*, the reduction in spatial variance of estimated values compared to true values.

3.1.20 *spatial average, n*—a quantity obtained by averaging a regionalized variable over a finite region of space.

3.1.21 *support, n—in geostatistics*, the spatial averaging region over which a regionalized variable is defined, often approximated by a point for sample-scale variables.

3.1.22 *universal kriging, n*—a form of kriging in which additional weighting constraints are introduced in order to account for a drift in the estimated variable.

3.1.23 *variogram, n*—a measure of spatial variation defined as one half the variance of the difference between two variables and expressed as a function of the lag; it is also sometimes referred to as the semi-variogram.

3.2 For definitions of other terms used in this guide, refer to Terminology D653 and Guides D5549, D5922, and D5924. A complete glossary of geostatistical terminology is given in Ref (**7**).

4. Significance and Use

4.1 This guide is intended to encourage consistency and thoroughness in the application of kriging methods to environmental, geotechnical, and hydrogeological site investigations.

4.2 This guide may be used to assist those performing a kriging study or as an explanation of procedures for qualified nonparticipants that may be reviewing or auditing the study.

4.3 This guide encourages the use of site-specific information for the selection of an appropriate kriging method; however, the quality of data, the sampling density, and site coverage cannot be improved or compensated by any choice of kriging method.

4.4 This guide describes conditions for which kriging or particular kriging methods are recommended. However, these methods are not necessarily inappropriate if the stated conditions are not encountered.

4.5 This guide should be used in conjunction with Guides D5549, D5922, and D5924.

5. Selection of Kriging Methods

5.1 The following subsections describe conditions for which various kriging methods are appropriate. Each section corresponds to a step in a geostatistical site investigation where a decision concerning the most appropriate form of kriging may have to be made. Ordinary kriging is the most common form of kriging and is the conventional default unless any of the following conditions makes another method more appropriate.

5.2 *Study Objectives*—A common objective of geostatistical site investigations is to produce a two- or three-dimensional spatial representation of a regionalized variable field from a set of measured values at different locations. Such spatial representations are referred to here as maps. Estimation approaches, including all forms of kriging, yield maps that exhibit a smoothing effect, whereas simulation approaches yield maps that preserve the spatial variability of the regionalized variable.

5.2.1 If mapped values of the regionalized variable are required to provide a least-squares estimate of actual values at unsampled points, then a kriging method is appropriate.

5.2.2 If mapped values of the regionalized variable are to preserve the spatial variability of values at unsampled points, then simulation rather than kriging should be used.

NOTE 1—Preservation of in-situ spatial variability is important if mapped values of the regionalized variable are to be entered in a numerical model of a dynamic process and therefore simulation should generally be used. For example, mapped values of transmissivity to be entered in a numerical model of groundwater flow should not be generated by kriging since this may produce spurious flow patterns (**6, 7**). However, if the numerical process model is insensitive to spatial variations of the regionalized variable, then kriging methods may also be used.

5.2.3 If an objective of the study is to generate multiple possible outcomes of a regionalized variable field for the purpose of risk analyses or sensitivity studies, then kriging methods are inappropriate and simulation approaches are recommended.

5.2.4 If an objective of the study is to estimate probability distributions for regionalized variables over an entire field, as required for calculating site-wide compliance probabilities, then kriging methods are inappropriate and simulation approaches are recommended.

5.2.5 If an objective of the study is to provide the best linear unbiased estimate of a regionalized variable at unsampled locations, and the mean is assumed constant but unknown, then ordinary kriging is the appropriate estimation method.

5.2.6 If an objective of the study is to provide the best linear unbiased estimate of a regionalized variable at unsampled locations, and the mean is presumed known, then simple kriging is the appropriate estimation method.

NOTE 2—However, knowledge of the mean is an assumption seldom justified unless the mean can be confidently represented by some prior deterministic model. The model for the mean is then used to remove trends in the original data leaving the residuals with a mean of zero.

5.2.7 If an objective of the study is to quantify uncertainty using the kriging variance and data are adequately represented by a Gaussian distribution, then ordinary or simple kriging are appropriate estimation methods.

5.2.8 If an objective of the study is to quantify uncertainty using the kriging variance and log-transformed data are adequately represented by a Gaussian distribution, then ordinary or simple lognormal kriging are appropriate estimation methods.

5.2.9 If an objective of the study is to quantify uncertainty and data are not adequately represented by a Gaussian distribution, then the use of kriging variances is not appropriate, and indicator kriging is the preferred estimation method.

5.3 *Choice of Regionalized Variable*—The choice of regionalized variable made at the beginning of a geostatistical site investigation may affect the selection of an appropriate kriging method.

5.3.1 If the regionalized variable is binary or categorical, then indicator kriging is an appropriate estimation method.

5.3.2 If the regionalized variable has the same support as the sample data, then point forms of kriging are appropriate.

5.3.3 If the regionalized variable is additive and has a block support, and the data have a point support, then block forms of kriging are appropriate.

NOTE 3—However, if indicator or log-transformed regionalized variables are considered, then estimated block values should be interpreted with caution.

5.4 *Exploratory Data Analysis*—Exploratory data analysis during a geostatistical site investigation often reveals features of the data probability distribution function that affect the selection of an appropriate kriging method.

5.4.1 If log-transformed data are approximately Gaussian, then lognormal kriging may be an appropriate estimation method.

5.4.2 If the data include extreme values that cannot be treated as spatial outliers or separate populations, then indicator kriging is an appropriate estimation method.

NOTE 4—However, if the data are skewed and this skewness is caused by only a few outliers or clustered sampling, then ordinary kriging remains an appropriate estimation method.

5.5 *Analysis of Spatial Variation*—Analysis of spatial variation during a geostatistical site investigation often reveals features of the data spatial variability structure that affect the selection of an appropriate kriging method.

5.5.1 If the analysis of log-transformed data reveals a better-defined spatial variation structure than an analysis of the original data, then lognormal kriging may be an appropriate estimation method.

5.5.2 If calculated indicator variograms for different thresholds exhibit different patterns of spatial variability other than high nugget effects at extreme thresholds, then indicator kriging is an appropriate estimation method.

5.5.3 If a drift is present and spatial extrapolation of data is desired, then a drift model is required, and universal kriging is an appropriate estimation method.

NOTE 5—However, if a drift is present and the drift can be accommodated by adjusting the configuration of the search neighborhood, then ordinary kriging remains an appropriate estimation method.

6. Keywords

6.1 estimation; geostatistics; kriging; simulation

REFERENCES

(1) Journel, A. G., and Huijbregts, C., *Mining Geostatistics*, Academic Press, London, 1978.

(2) Isaaks, E. H., and Srivastava, R. M., *An Introduction to Applied Geostatistics*, Oxford University Press, New York, 1989.

(3) Marsily, G. de, *Quantitative Hydrogeology*, Academic Press, Orlando, 1986.

(4) ASCE Task Committee on Geostatistical Techniques in Geohydrology, "Review of Geostatistics in Geohydrology," (1), Basic Concepts, (2) Applications, *ASCE Journal of Hydraulic Engineering*, Vol 116, No. 5, 1990, pp. 612–658.

(5) Olea, R. A., ed., *Geostatistical Glossary and Multilingual Dictionary*, Oxford University Press, New York, 1991.

(6) Desbarats, A. J. and Dimitrakopoulos, R., "Geostatistical Modelling of Transmissibility for 2D Reservoir Studies," *SPE Formation Evaluation*, Vol 5, No. 4, 1990, pp. 437–443.

(7) Hewett, T. A., "Fractal Distributions of Reservoir Heterogeneity and Their Influence on Fluid Transport," *SPE Paper 15386*, Presented at the 1986 SPE Annual Technical Conference and Exhibition, New Orleans, LA, Oct. 5–8.