

Geostatistics in Geotechnical Engineering: Fad or Empowering?

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Abstract

Geotechnical engineering by its nature demands tools for coping with large uncertainties and variations in material properties. One such tool, which the profession has tried to adopt, is geostatistics. This paper examines the question of whether geostatistics really holds much promise for geotechnical engineering, and attempts to identify conditions that if satisfied could convert geostatistics into a real design aid for geotechnical engineers.

The paper briefly looks at the origins of geostatistics, and examines its successful application to a variety of fields. It also describes the potential benefits geostatistics can bring to geotechnical engineering, and explores possible reasons underlying geotechnical engineering's difficulties in fully harnessing the power of the method. The paper conjectures that primary reasons include widespread unfamiliarity with the concepts of geostatistics, and a lack of geostatistical software tools that can be readily used in geotechnical analysis.

Introduction

Geotechnical engineering is constantly evolving and its practitioners are always looking out for tools, which can improve design and help better handle the large uncertainties and variations inherent in soil and rock properties. In recent years, several authors have attempted to apply geostatistics to the problems of geotechnical engineering. But does this field hold promise for geotechnical engineering?

To help track the evolution of the interest of geotechnical engineers in geostatistics, the authors conducted a simple survey of geotechnical engineering papers that listed "geostatistics" in their titles, abstracts, descriptions or keywords. The search covered the period from 1970 to 2003. Sixty-four such publications were found. They were sorted by year of publication, and the results summarized in the form of a histogram (see Figure 1).

The histogram indicates that up until 1978, no papers listed their focus (as per the definition above) as geostatistics and geotechnical engineering. Over the rest of the period interest seems to rise and fall a few times. Currently interest appears to be at another low. Will there be another peak, or are we seeing the end of geotechnical interest in geostatistics? If there is indeed a lack of interest, what reasons lie behind the indifference? Doesn't geostatistics offer the profession significant benefits? These questions are not easily answered, certainly not from our simple analysis. However, we believe that whatever the answers are, there are things that can be done to ensure that geotechnical engineering fully benefits from the power of geostatistics. This paper will describe ways in which geostatistics has been used to great effect in the geotechnical profession, and will describe some of the things that can be done to help establish widespread acceptance of geostatistics in the profession.

It is the thesis of this paper that should geotechnical engineering be able to fully appreciate the power of geostatistics, and understand its concepts and tools, it will benefit tremendously. Should the profession be unable to do so soon, successful application of the method might be delayed for a period, an outcome we deem unfortunate and unnecessary. Regular reports on geostatistics in geotechnical engineering publications will:

- Help educate the general profession on its benefits and stimulate critical thinking on its methods
- Encourage many to try it, and
- Provoke creative application to a wide range of problems.

We believe that since geostatistics has so much to offer to geotechnical engineering, there are compelling reasons to adopt its approaches now.

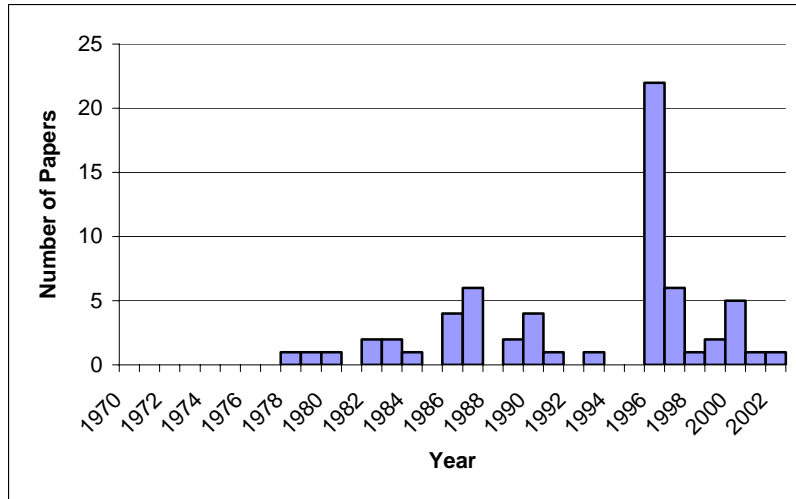


Figure 1. Histogram of the frequency of geotechnical publications on geostatistics over the last 33 years.

What is Geostatistics?

Geostatistics deals with spatial data, i.e. data or properties associated with locations in space. It is assumed in such analyses that there is some connection between location and data values. From known values at sampled points, geostatistical analysis can be used to predict spatial distributions of properties over large areas or volumes.

To determine geotechnical and geological conditions, such as the stratigraphy of soil or rock layers, at a project site, boreholes are drilled at some specified locations. Very often, and as expected, one finds that measurements from boreholes near to each other tend to be more similar than those from widely separated boreholes. This observation forms the basis of the fundamental geostatistics assumption of links between location and measured properties.

In what way does geostatistics differ from conventional statistics? Conventional statistics generally analyzes and interprets the uncertainty caused by limited sampling. For example, a statistical analysis of core samples from a site investigation program might show that measured cohesion values can be described by a normal distribution. However, this distribution only describes the population of values gathered; it does not offer any information on which zones are likely to have high cohesion values and which areas low values.

Geostatistical analysis, on the other hand, examines spatial relationships in addition to establishing statistical distributions of data. For the example given, geostatistics can reveal how cohesion varies over distance, and can predict localized zones of high and low cohesion values. It provides tools for maximizing the information captured from sparse, often biased, and often under-sampled sample data. Ultimately it predicts probable distributions of properties in space.

We believe that the geotechnical engineering should strongly consider adopting the techniques of geostatistics. Broad-based application of geostatistics will lead to more ready incorporation of the inherent uncertainty of soil and rock masses into numerical models and into the design process in general.

Ways in which Geostatistics can Benefit Geotechnical Engineering

To help appreciate what geostatistics can do for geotechnical engineering, we shall take a brief look at the origins of the discipline and examine its successful application to a variety of fields. The method was originally conceived in the 1960's as a methodology for estimating recoverable reserves in mining deposits. Today it is extensively used in the mining and petroleum industries, and in recent years has been successfully integrated into remote sensing and Geographic Information Systems (GIS).

The problem in reserve estimation is this: decisions on very costly expenditure have to be made based on very sparsely sampled information. Typically, the ratio of the volume of samples recovered from exploration boreholes to the volume of an ore deposit is on the order of 1×10^{-9} ! Yet on this information recoverable reserves have to be reliably estimated, and decisions made on investing large sums of money into developing the deposit.

Although the financial costs of the average geotechnical project may not be as high as those of exploration projects, geotechnical site investigations face similar hurdles. In almost every geotechnical project, the volume of samples extracted for characterizing soil or rock masses constitutes only a minute fraction of the volume of material that impacts engineering behaviour. Like the properties measured in resource exploration, the engineering properties of soil and rock masses are heterogeneous, varying from location to location. Important decisions with major implications on total project costs have to be made on the basis of the sparsely sampled data.

What do geotechnical engineers typically do with the data they collect? Either for the sake of simplicity or for lack of appropriate tools, engineers assume properties to be the same throughout a domain, and assume material layers and boundaries to be linear between sampling points. It is however well known that use of averaged parameter values can lead to conclusions, which significantly differ from actual behaviour, and it is acknowledged that more accurate knowledge of the spatial distribution of material properties promotes safe and economic design. Given the potential improvements to design and the successes of geostatistics in resource estimation, we believe that geotechnical engineering should seriously consider the geostatistical tools. They will facilitate more accurate interpretation of ground conditions based on the sparse information that characterizes geotechnical investigations.

Among many other benefits, geostatistical analysis can offer the following to geotechnical engineering:

1. Powerful tools for forming relatively simple, yet accurate, models of inhomogeneous material based on limited sample data
2. Techniques for optimizing sampling locations so that maximum information can be obtained at minimized cost, and
3. Methods for estimating engineering properties at different locations with minimum estimation error.

In the next few lines we shall briefly examine two of these potential benefits.

Optimization of Site Investigation Locations

The most immediate benefits of the application of geostatistics to geotechnical engineering lie in the optimization of site investigation sampling locations. A most challenging task in site investigation is to design a minimal cost sampling program that best captures information on underground conditions. The site investigator is often required to answer the question, "Should more ground investigations be conducted, will the additional information obtained justify the extra cost or project delay?" In most situations she does not have the tools to adequately answer this question.

Geostatistics provides spatial modelling tools that can help answer the above-posed question. It can create maps that show the distribution of properties over an area or volume. These digital maps provide the most accurate estimates of spatial distributions of sampled properties.

Another very useful outcome of geostatistical analysis is the contour plots of the standard deviations of predicted values at non-sampled locations. These contours identify areas of higher uncertainty – the higher the standard deviation the greater the uncertainty. Knowing this, engineers can then acquire additional samples from these locations to substantially improve understanding of subsurface conditions.

Three-dimensional visualization of property variability in space is another great benefit of geostatistical analysis. Properly implemented in software, such analysis permits different hypotheses and assumptions on variability to be readily tested. This makes it possible to establish likely spatial distributions, and from that determine which interpretations are most consistent with experience in a locale or with some form of geological theory.

Simulation and Numerical Modelling

Geostatistical simulation can help geotechnical engineers assess the risks posed by uncertainty. Such simulation can produce many, equally likely, spatial representations of a parameter in a manner consistent with values observed at sampled locations and with *in situ* variability. The differences between alternative models provide a measure of spatial uncertainty. The spatially distributed realizations of a variable can then be input into numerical models and used to evaluate risks.

Geostatistical simulation has been used to study the hydrology of fractured rock masses. In these studies, different three-dimensional fracture networks are generated, and then analyzed for flow patterns. Simulation can be also applied to stress analysis problems. In finite element analysis, for example, each element in a model can be assigned unique deformation and strength properties. Using geostatistics, element properties can be assigned in a manner that realistically reflects heterogeneity at a site. Studies have shown that the results of such analyses can differ substantially from those obtained from conventional computations, which use simple averaged values.

Successful Application of Geostatistics to Channel Tunnel Project

Among the many factors that made the success of the Channel Tunnel project possible, geostatistics has been deemed to be one of them. It enabled the careful assessment of geological risks, and was used to optimize the alignment of the tunnel.

Figure 2 shows a typical geological cross-section of the seabed through which the tunnel was excavated. In selecting an optimal alignment for the tunnel, a governing criterion was to ensure that the tunnel was bored only within the Chalk Marl, avoiding the Gault Clay material. Kriging, a geostatistical technique, was used to determine the boundary between the Chalk Marl and the Gault Clay, based on data available prior to construction. Contours of the standard deviations of predicted depths of this boundary were also generated.

The geostatistical analysis enabled engineers to improve the tunnel's alignment. The standard deviation contours helped identify tunnel sections at which improved precision was required, which in turn enabled design of successful complementary geophysical surveys of the seafloor. As data became available from these surveys and ongoing construction, tunnel engineers used geostatistics to repeatedly improve the spatial model of the Chalk Marl–Gault Clay interface.

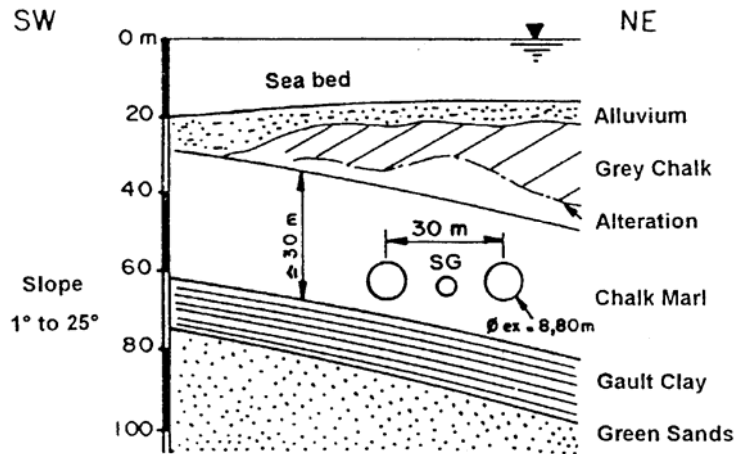


Figure 2. Geological cross-section through the seafloor of the Channel Tunnel (taken from Reference [1]).

The result was that Channel Tunnel engineers were able to keep the risks of penetrating the Gault Clay at acceptable levels, and were able to achieve their objectives of avoiding the Gault Clay formation. Penetration of the Gault Clay occurred only twice. On both occasions these areas had been already predicted from the geostatistical model and so did not pose surprises. At the end of the project, when the actual locations of the Chalk Marl–Gault Clay boundary were compared to predictions from the geostatistical model, the two were found to be in good agreement. If there were any doubters to the usefulness of geostatistics for geotechnical engineering, this project should have helped ease their fears.

Conjectures on the Reluctance of Geotechnical Engineers to Adopt Geostatistics

The authors have not fully analyzed the reasons why geostatistics has not received routine application in geotechnical engineering. However, they suspect that the single biggest reason is unfamiliarity of geotechnical engineers with the concepts of geostatistics. Mining and petroleum exploration specialists are well schooled in geostatistical analysis, and are very familiar with its power and benefits. As a result they are inclined to use the method as soon as the opportunity beckons or the need arises.

The typical geotechnical engineer, on the other hand, having had hardly any exposure to geostatistical theory, is not so willing to venture into such territory. Even when he is in a position to perform such analysis, he may not know how or may not have the means to incorporate the information into geotechnical analysis.

What can be done to Facilitate Adoption of Geostatistical Analysis?

For the geotechnical profession to fully exploit the advantages and power of geostatistics appropriately adapted tools are required. There is also a need to develop a tradition of applying the discipline. The obvious starting point for bringing geostatistics into mainstream geotechnical engineering practice is through education, education on the basic principles, areas of application and advantages. To us, site investigation seems to be the area best suited for introducing geotechnical engineers to geostatistics. The goals and challenges of field investigations are so similar to those of resource estimation.

The learning of geostatistics in geotechnical engineering can be accelerated through easy-to-use, intuitive software tools. Unfortunately this means the development of new software programs specifically aimed at the geotechnical engineer. Most existing geostatistical software modules are buried within huge mining-oriented programs that can handle many other problems such as mine-scheduling, pit design, etc. This poses three primary challenges:

- A steep learning curve involving study of material completely unnecessary to the geotechnical engineer
- Analysis results, which are not readily incorporated into subsequent geotechnical calculations, and
- Expensive costs of purchasing.

Geostatistical software tools, customized to the needs of the geotechnical engineer, will greatly minimize the time and effort required to understand of the principles of geostatistics, and significantly reduce the effort required to apply them.

Geostatistical analysis tools, appropriately implemented software, will facilitate powerful and interactive visualization of spatial distributions of geotechnical properties. This will enhance correct interpretation of subsurface conditions. Such software will also enable and encourage exploration of alternative assumptions and interpretations regarding ground conditions.

Easy export of the spatial variability into numerical models will allow geotechnical engineers to more readily evaluate the dangers posed by the uncertainties in subsurface conditions. Through what-if scenarios – what happens when conditions are not the same as what we've assumed them to be? – they can gain invaluable insights into potential and observed behaviour. Routine application of such techniques will instil a discipline of significant value into the design process.

Given the levels of financial and resources devoted to field investigations and data collection, and the implications and costs of being wrong about conditions gleaned from sparsely sampled data, geotechnical engineering will be well served by adopting geostatistics. It is our hope that this article will catch the attention of some keen minds, minds willing to accept the challenge of harnessing the power of geostatistics for geotechnical engineering. The profession will greatly benefit from such pioneering efforts.

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