Geostatistics

An article outlining the issues that affect the use of geostatistics in geotechnical engineering analysis. The profession needs to fully appreciate the power of the method, understand its concepts and tools, and make its use part of routine geotechnical analysis.

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Geostatistics in Geotechnical Engineering:
A fad or an empowering approach?

Geotechnical engineering is constantly evolving and its practitioners always on the lookout for tools, which improve design and help better cope with the large uncertainties and variations in soil and rock properties.

In recent years, several authors have attempted to apply geostatistics to the problems of geotechnical engineering. Does this field hold promise for geotechnical applications? Geotechnical engineering is constantly evolving and always seeking for tools, which improve design and help better cope with the large uncertainties and variations in soil and rock properties. In recent years, several authors have attempted to apply geostatistics to the problems of geotechnical engineering. Does this field hold promise for geotechnical applications?

To help track the evolution of the interest of geotechnical engineers in this science, we 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. It found 64 such publications. We then sorted the outcome by year of publication and created a histogram (Figure 1) of the resulting table.

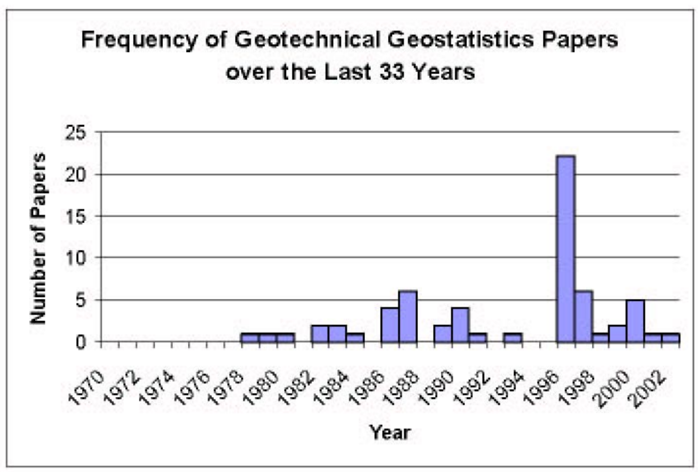

Figure 1 - A histogram plot of the frequency of geotechnical publications on geostatistics over the last 33 years

The histogram indicates that up until 1978, no paper existed that listed its focus as geostatistics and geotechnical engineering. Over the rest of the period, interest seems to peak and fall a few times, and currently interest appears to be at another low. Is there going to be another peak or are we seeing the end of interest in geostatistics? Why is geotechnical engineering losing interest in geostatistics? Does it not offer the profession significant advantages? These are just a few of the questions that beg to be asked from our simple analysis.

We believe that the profession is at a crossroads with regards to geostatistics. If the profession is able to fully appreciate the power of the method and understand its concepts and tools, geotechnical engineering will benefit tremendously. If the profession is unable to soon harness the power of geostatistics, application of the method might again be shelved, at least for a while. We believe that Rocscience can contribute in a way that helps ensure successful use of geostatistics in routine geotechnical analysis.

What is Geostatistics?

Geostatistics deals with spatial data, i.e. data for which each value is associated with a location in space. In such analysis it is assumed that there is some connection between location and data value. 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 assumption in geostatistics that location has a relationship to measured properties.

In what way does geostatistics differ from conventional statistics? Statistics generally analyzes and interprets the uncertainty caused by limited sampling. For example, a conventional statistical analysis of core samples from a site investigation program might show that measured cohesion values

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of a material can be described by a normal distribution. However, this distribution only describes the population of values gathered in the investigation; 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, interprets statistical distributions of data and also examines spatial relationships. For the example given, it is capable of revealing how cohesion values vary over distance, and of predicting areas of high and low cohesion values. The discipline provides tools for capturing maximum information on a phenomenon from sparse, often biased, and often under-sampled data. Ultimately it produces predictions of the probable distribution of properties in space.

We believe that the geotechnical engineering profession should give strong consideration to adopting the techniques of geostatistics. Wide application of the discipline will lead to more ready incorporation of the inherent uncertainty of soil and rock masses into numerical models and the design process.

How can geostatistics benefit geotechnical engineering?

To help appreciate what geostatistics can do for geotechnical engineering, let us 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 GIS.

The problem in reserve estimation was that decisions on very costly expenditure had to be made based on very sparsely sampled information. The ratio of the volume of samples recovered from exploration boreholes to the volume of a deposit of interest was often of the order of 1×10^{-9}! Yet on this information recoverable reserves had to be reliably estimated, and decisions made on investing large amounts 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 engineering has similar concerns. In almost every geotechnical project, the volume of samples obtained for characterizing soil or rock masses constitutes only a minute fraction of the volume of material that impacts design and behaviour of proposed structures. Just like the attributes measured in resource exploration, the engineering properties of soil and rock masses are heterogeneous, with properties varying from location to location. In addition, the financial resources committed to geotechnical field investigations often represent a significant portion of total project costs.

Regularly, either for the sake of simplicity or for lack of information, geotechnical engineers assume that properties are the same throughout a material domain. However, they know that the use of averaged parameter values can lead to conclusions that significantly differ from true behaviour, and recognize that accurate knowledge of the spatial distribution of soil and rock mass 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 discipline. Geostatistics will facilitate accurate interpretation of ground conditions based on the sparse input information characteristic of geotechnical engineering.

Among its many potential benefits to geotechnical engineering, geostatistical analysis offers the following:

- Powerful analytical tools for forming relatively simple, yet accurate, models of inhomogeneous material based on limited sample data
- Approaches for optimizing sampling locations so that they maximize the amount of information at minimized cost
- Techniques for estimating engineering properties at different locations with minimum estimation error.

We shall briefly examine some of these potential benefits.

Given the potential improvements to design and the successes of geostatistics in resource estimation, geotechnical engineering should embrace the discipline.

Optimization of Site Investigation Locations

In our opinion, the most immediate benefits of applying 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, “If more ground investigation is to be done, will the additional information acquired justify the extra cost or delay?”

Geostatistics provides spatial modelling tools that can help answer these questions. Geostatistical analysis can create maps that show the magnitude and distribution of the values of a parameter over an area or volume. These digital maps provide estimates, which most accurately estimate the spatial distributions of sampled properties.

Contour plots of the standard deviations of predicted values at non-sampled locations are a very useful outcome of geostatistical analysis. These contours show areas of higher uncertainty (higher standard deviations). Sampling from these locations can substantially improve the accuracy of predictions.

The tools of geostatistics enable the spatial variability of properties to be visualized. They also allow different hypotheses and assumptions on variability to be readily tested. This makes it possible to establish the most likely structure of spatial variability and determine from a variety of interpretations the ones most consistent with the available data.

Simulation and Numerical Modelling

Geostatistical simulation can help geotechnical engineers assess uncertainty and risks in design. It produces many, equally likely, digital spatial representations of a parameter that are consistent with values 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 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 also be applied to stress analysis problems. In finite element analysis, for example, each element in a model can be assigned its own deformation and strength properties. It is possible to assign different properties to different elements in a manner that realistically reflects the true conditions and heterogeneity of a soil or rock mass using geostatistics. Studies have shown that the results of such analyses can differ substantially from those obtained from analyses that employ 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 was deemed to have played a significant role. 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. One of the most important criteria in optimizing the alignment was to ensure that the tunnel was bored 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 before construction. Contours of the standard deviations of predicted depths of this boundary were also generated. As a result of the geostatistical analysis, engineers were able to improve the originally proposed alignment of the tunnel. The standard deviation contours helped engineers to realize that improved precision was required at certain tunnel sections, as a result of which they were able to design a complementary geophysical survey of the seafloor. As more data became available from surveys and ongoing construction, geostatistics enabled the tunnel engineers to readily improve the spatial model of the Chalk Marl–Gault Clay interface.

Engineers were able to improve the originally proposed alignment of the tunnel using geostatistical analysis.

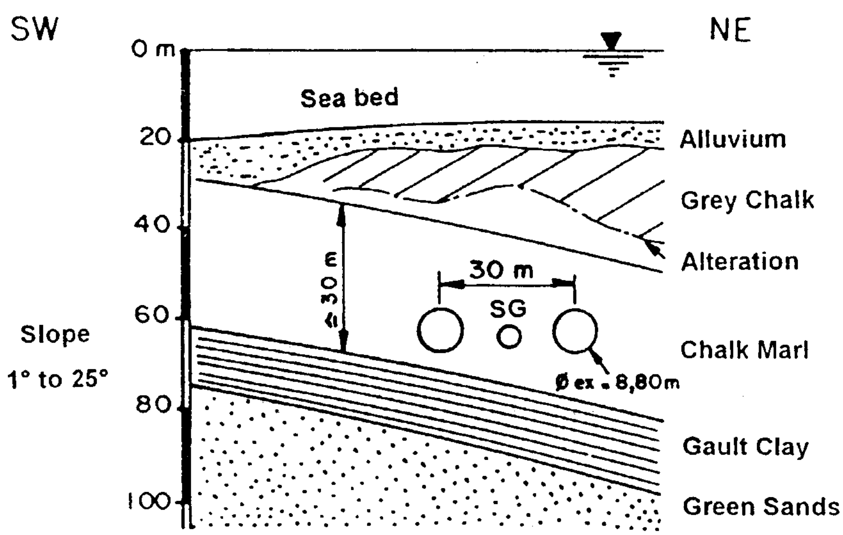

Figure 2 - Geological cross-section through the seafloor of the Channel Tunnel (taken from Reference [2]).

With the help of geostatistical analysis, engineers of the Channel Tunnel were able to maintain risks of penetrating the Gault Clay at acceptable levels and to achieve their objectives of avoiding the Gault Clay formation. Penetration of the Gault Clay occurred only twice and in areas that had been already predicted from the geostatistical model. At the end of the project when engineers compared actual locations of the Chalk Marl-Gault Clay boundary to the predictions from the geostatistical model, they found the two to be in good agreement. If there were any doubters to the usefulness of geostatistics to geotechnical engineering, this project should have helped put their fears to rest.

The reluctance of geotechnical engineers in adopting geostatistics

We have not fully analyzed the reasons why geostatistics has not become a routine application in geotechnical engineering. However, we believe that one of the biggest reasons could be widespread unfamiliarity with the concepts of geostatistics. As well, the theoretical complexity and the effort required to perform a geostatistical study could be factors.

Many of the existing geostatistics software tools are not formulated in ways that can be readily integrated into geotechnical analysis. This makes geotechnical engineers unwilling to make the time and effort commitments required to learn to use the method.

What can Rocscience do to facilitate routine geotechnical geostatistical analysis?

For the geotechnical profession to fully exploit the advantages and power of geostatistics, it requires appropriately adapted tools, and needs to develop a tradition of applying the discipline. A natural starting point for bringing geostatistics into mainstream geotechnical engineering practice seems to be through application to site investigations.

Given Rocscience's success in developing geotechnical engineering software, the company can play a vital role in helping the profession to adopt geostatistics. The company can create easy-to-use geostatistical software tools specifically developed for the geotechnical engineer. Organized intuitively, such tools will greatly minimize the time and effort required to understand the principles of geostatistics, and significantly reduce the effort required to apply them.

Geostatistical analysis tools, appropriately implemented in the company's suite of user-friendly applications, will facilitate powerful and interactive visualization of the spatial distributions of geotechnical parameters. It will aid in the correct interpretation of data. Such software will also enable and encourage exploration of alternative assumptions and interpretations in the analysis of ground conditions. Through export of the spatial distribution of geotechnical properties, geostatistical software for geotechnical engineers will allow them to realistically incorporate inherent spatial variability into numerical models.

Given the levels of financial and other resources devoted to field investigations and data collection, and which already capture the inherent spatial variability of soil and rock masses, geotechnical engineering will be well served by adopting geostatistics. Rocscience is prepared to play a role.

NB: If you have any comments, questions or ideas on geostatistics and its usefulness to geotechnical engineering, you may email your thoughts to: geostatistics@rocscience.com

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