

## **Geotechnical Data Presentation and Earth Volume Estimates—Surveying in Three Dimensions**

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### **Abstract**

Current surveying practice—whether it employs the Global Position System (GPS), total station instrumentation, or laser scanning—involves the generation of a set of triaxial coordinates that spatially and mathematically define the project being mapped. Such data sets provide the surveyor with an opportunity to employ a variety of relatively new data presentation and computation techniques that facilitate entry into new market areas.

Three dimensional (3D) drawings of surveying projects are a relatively new method of mapping to most surveyors. While surveyors are aware that computer aided drafting (CAD) software has 3D capabilities, few have exploited this method of data representation. Similarly, computation of earth volumes is a common part of heavy construction cost estimating because volume estimates form the basis for planning equipment assignments, estimating excavation and embankment activity times for the project schedule, and determining the quantities of borrow or waste that must be purchased or disposed of during construction.

This research addresses two questions: (1) How can geotechnical data be simply presented in three dimensional format that benefits the data user? and (2) how can earth volume computation be expedited using current field techniques and software?

Using both hypothetical and actual field data, the authors suggest several ways in which three dimensional subsurface data can be generated efficiently and used in a production environment. Methods of computing intersurface volumes for different earth materials are evaluated and techniques discussed for preventing mistakes in data computation and presentation.

### **Introduction**

Current surveying practice—whether it employs the Global Position System (GPS), total station instrumentation, or laser scanning—involves generation of triaxial coordinates that spatially and mathematically define the project. Such data provide the surveyor with an opportunity to employ a variety of relatively new drafting and computation techniques that facilitate entry into new market areas.

Three dimensional (3D) drawings of surveying projects are a relatively recent method of mapping to most surveyors. While surveyors are aware that computer aided drafting (CAD) software has 3D capabilities, few have exploited this method of data representation. This is surprising, because the importance of visualizing the subsurface has been recognized for some time in the energy industry as a means of minimizing risk. Such visualization has not received the same attention in the surveying and construction sectors, however, despite the fact that visualization of the geotechnical situation on a job site not only is important in foundation design, but is central to the planning of excavation and embankment as well.

Similarly, computation of earth volumes is process well known to surveyors. Such computations are a common part of heavy construction cost estimating because volume estimates form the basis for planning equipment assignments, estimating excavation and embankment activity times for the project schedule, and determining the quantities of borrow or waste that must be purchased or disposed of during construction.

Three dimensional drawing and volume computation come together in the geotechnical drawings and report employed as part of the construction planning and design process, while drilling logs provide the basis for defining the surfaces and computing the volumes of the different materials encountered by the drilling crew on the job site. This intersection of 3D drawing and intersurface volume computation provides an opportunity to facilitate better visualization of subsurface conditions than is typically employed at present. While technically conversant persons can visualize a site from two dimensional drawings, inexperienced persons are not so adept.

The purpose of this research is to investigate how triaxial data sets typical of current survey practice can be used to generate 3D drawings and to compute intersurface volumes. Specifically, the following questions are addressed:

- (1) How can geotechnical data be simply presented in three dimensional format that benefits the data user? and
- (1) How can earth volume computation be expedited using current field techniques and software?

### **Previous Work**

Basic survey drafting principles are discussed in numerous texts (Kavanagh, B.F., 2001; Madsen & Schumaker, 2004; Schofield, 2001; Wolf & Ghilani, 2006). These authors properly stresses lettering styles, line weights, map arrangement, and graphic content (Kavanagh, B.F., 2001; Madsen & Schumaker, 2004; Schofield, 2001; Wolf & Ghilani, 2006). However, little attention is generally given to 3D representation of surveying projects.

Architects routinely use CAD-generated three dimensional renderings as presentation tools, and use of parametric modeling is common in manufacturing applications. Cross-over of this technology into the construction field is evidenced by the increasing use of

3D drawings for the mechanical construction plans on major projects. While a number of survey software packages provide 3D mapping capabilities, 3D mapping has yet to be utilized on a production basis by most surveyors. There is, in consequence, much to be learned about 3D mapping and data presentation methods. This includes not only 3D representation itself, but questions of scale, vertical exaggeration, color, and pattern.

The subject of earthwork volume estimates is discussed in most basic surveying texts (Kavanagh, B.F., 2001; Schofield, 2001; Wolf & Ghilani, 2006) as well as in texts on construction cost estimating (Bartholomew, 2000; Dagostino & Feigenbaum, 2003; Nunnally, 2007). Classic field and office methods for volume estimation include the borrow-pit (or checkerboard) method and the average end area method. Both employ specific field procedures in support of computation (Kavanagh, B.F., 2001; Schofield, 2001; Wolf & Ghilani, 2006; Bartholomew, 2000; Dagostino & Feigenbaum, 2003; Nunnally, 2007).

Current survey field practice, however, employs triaxial coordinates that can be used to prepare a digital elevation model (DEM) of the site that can serve for volume computation (Wolf & Ghilani, 2006). The DEM can be considered as the surface of a mathematical function. The general equation for the volume under a function can be written as

$$V = \int_{x1}^{x2} \int_{y1}^{y2} f(x, y) dx dy , \dots\dots\dots(1)$$

where V = volume; f(x,y) = function; and dx, dy refer to the spacing of points in the x and y directions respectively (Surfer, 2002). The accuracy of the computed volume depends on the accuracy and density of the data employed. The precision of the volume computation depends on the size of the intervals  $dx$  and  $dy$ ; the smaller the spacing, the more precise the computation.

## Methods and Procedure

The research described herein involved volume estimates and three dimensional drawings based on data typically obtained from a combined site survey and geotechnical investigation. These data normally include the following three elements: (a) a surface topographic survey and associated set of points (X,Y,Z) defining the existing surface; (b) drill hole location (X,Y,Z) based on a field survey; and (c) drilling data (X,Y,Z<sub>n</sub>,Z<sub>(n+1)</sub>) showing depths and materials logged at each drill hole by the drilling crew.

**3D drawings.** In this research, data for three study areas were used to test contouring, volume computation and data presentation techniques using a simple software package. Study area 1 was a relatively simple site on which it was assumed that monthly volumetric production of aggregate was to be determined. Study area 2 was a hypothetical site for which it was assumed that geotechnical drilling has been completed and for which volumes of multiple materials were to be obtained. Study area 3 was a

public project on which geotechnical data was available and for which general techniques developed on study areas 1 and 2 were evaluated for use on an actual project.

The software package used in this project was Surfer (version 8) by Golden Software, Golden, Colorado. This software was used because of its availability to the investigators and because of their familiarity with it. This software provides the user with the opportunity to import triaxial coordinate data typically obtained by field survey as discussed above. The function  $f(x,y)$  in equation (1) is approximated from field or drill hole data by mathematically generating a set of points on a regular grid across the site. This is done using any of a variety of gridding algorithms (Surfer, 2002). Grid dimensions define the size of the intervals  $dx$  and  $dy$ . Separate surfaces can be generated from the grid files for each type of material shown by the drill logs. The resulting grid files are then used to prepare topographic maps and cross sections, three dimensional surface plots, and volume estimates.

Naturally, the topographic surface produced in mapping and the intersurface volumes computed for each subsurface material are influenced by the gridding algorithm used. Mapping conducted in this research employed the Kriging algorithm only. However, the impact of three different algorithms on the resulting volume computation was investigated. The algorithms employed included (a) a triangulated irregular network (TIN) algorithm, (b) the Kriging algorithm, and (c) an algorithm employing the method of minimum curvature. These are discussed below because of their importance to this work.

The **TIN algorithm** is a linear interpolation algorithm familiar to most surveyors. Elevations at grid intersections are based on a series of triangular planes connecting observed points. When used for contouring, the resulting surface is realistic provided that the field crew has correctly located breakpoints on the surface. The assumption that subsurface drilling data represents subsurface breakpoints, however, is probably incorrect.

The **Kriging algorithm** interpolates grid elevations from the data set using weighted interpolation that is dependent on a function known as a variogram. This research used the default linear variogram, although different mathematical options are provided by Surfer for variogram definition. Unlike the TIN algorithm, Kriging (and its associated variogram) attempts to mathematically identify trends in the data set and represent the same in the gridded surface. To the extent that the trends noted accurately reflect subsurface conditions, the Kriging algorithm might be considered to be advantageous.

The **method of minimum curvature** attempts to define the surface involved based on use of a linearly elastic plate passing through the data points. The resulting grid is smoothed iteratively. Information on the mathematical formulae employed by these algorithms can be found in Surfer (2002), Smith and Wessel (1990), Journel and Huijbregts (1978), and Lee and Schachter (1980).

For each study area used in this research, field data for 3D mapping was the same as that used for volume computation. All mapping shown below was based on the Kriging algorithm, and volume computations were completed using all three algorithms.

**Volume computation.** Intersurface volume computation using Surfer (2002) is done using the grid file generated for each surface for a solution to equation (1). To solve equation (1) the area of each intersurface “slice” through the grid is computed and then used in computation of intersurface volume (Surfer, 2002). To provide a check for mistakes in data entry and to provide an evaluation of the precision of the computation, intersurface volumes in this research were computed using three different methods for each of the three gridding algorithms employed. These included the trapezoidal rule, Simpson’s 1/3 rule, and Simpson’s 3/8 rule. The equations for these are well known and are included in appendix A.

**Results and Analysis**

**3 D drawings.** Three dimensional drawings for all three study areas are shown in figures 1-4. The drawing shown were all prepared using a grid based on the Kriging algorithm.

Figure 1 shows the results of a hypothetical routine volume computation for a gravel pit constituting study area 1. The site employed was 300 feet by 300 feet. Field data consisted of observations on a 7 x 7 (49 point) grid 50 feet square. During gridding, a 200 x 200 element grid was developed with a point spacing of 1.5 feet. Topographic maps were prepared and overlain on the respective wireframe models to show the surface at the beginning and end of the inventory period, and volumetric data is summarized on the map proper rather than in a separate report.

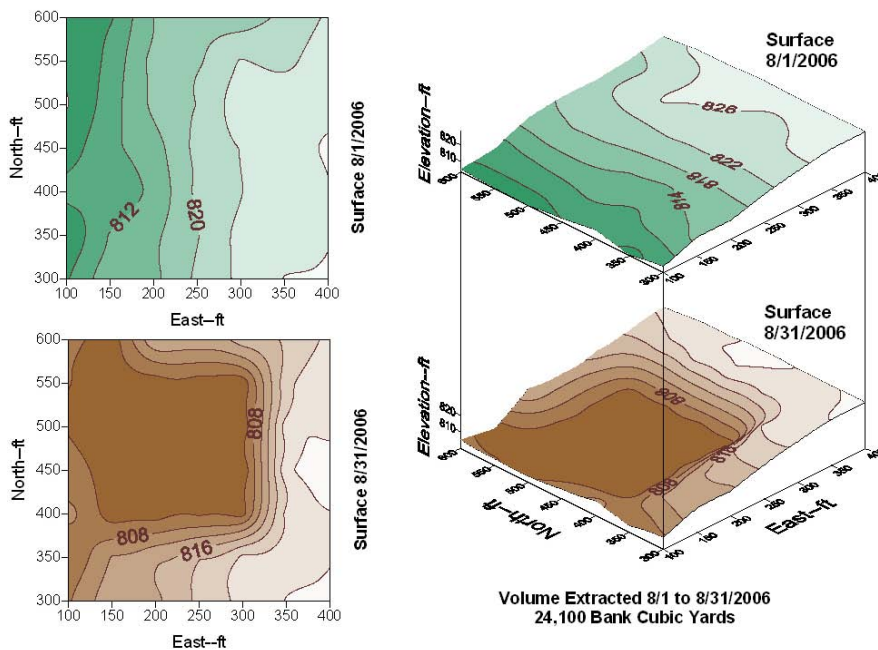


Figure 1. Simple volumetric survey.

Figure 2 shows the results of a hypothetical geotechnical investigation and volume computation on study area 2. The site involved was 500 x 500 feet. Field data consisted of observations at five drill holes that defined two material types: a surface layer of clayey sand (SC) and a subsurface layer of well graded gravel (GW). The two material types generated four surfaces with the base of the sandy clay being the same surface as the top of the well-graded gravel. During gridding, a 101 x 101 element grid was developed with a point spacing of 5 feet. Topographic maps were prepared and overlain on the respective wireframe models to show the surfaces and intersurface volumes. A difficulty encountered in working with figure 2 was the vertical separation of the surfaces involved. If a consistent vertical scale was maintained for the two surfaces, either the upper surfaces were so close together as to hide parts of the surfaces involved, or the lower surfaces were so far apart as to appear confusing.

A block diagram of the second study area is shown in figure 3. This diagram was made by developing and overlaying surface models based on drilling data. Volumes of both materials are shown on the drawing. As in figure 2, intersurface volumes were computed using the grid files of the surface and the clayey sand and the clayey sand and the well graded gravel. A difficulty encountered in working with figure 3 was the inability to

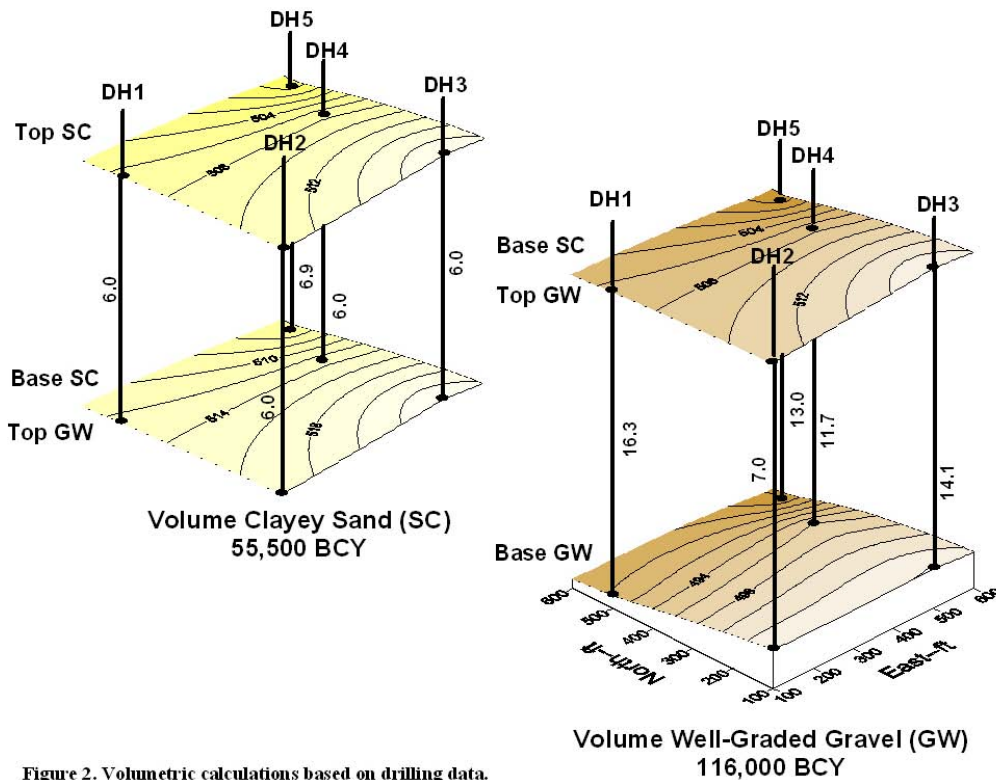
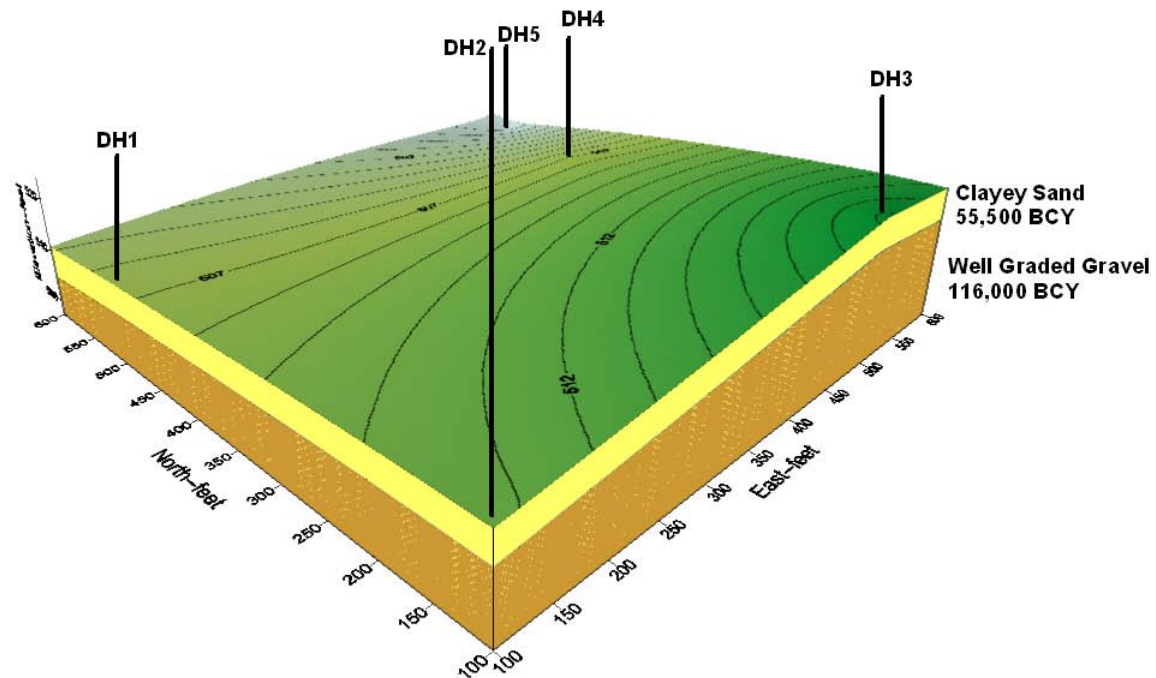


Figure 2. Volumetric calculations based on drilling data.



**Figure 3. Block diagram based on drilling data.**

show the intersurface location of the drill holes. This problem could be resolved by using software that provides “transparent” layers in the composite surface model.

Figures 4 and 5 show the results of an actual geotechnical survey on study area 3. The site involved was 700 x 500 feet. Field data consisted of observations at 14 drill holes. The material types included (1) a low plasticity clay (CL), (2) a poorly graded sand (SP), (3) a high plasticity silt (MH), and (4) a silty sand (SM). During gridding, a 141 x 101 element grid was developed with a point spacing of 5 feet. Topographic maps were prepared and overlain on the respective wireframe models to show the surfaces and the intersurface volumes. Figure 4 shows surfaces and intersurface volume for the low plasticity clay. In addition, a section has been generated across the site and shows the thickness of the clay layer. Figure 5 is a block diagram that shows the relationships of the four materials on site, as well as the results of volume computations for the top two layers.

While figure 4 and 5 nicely summarize site conditions, it was necessary to generalize much of the material on the geotechnical report that the drawings were intended to illustrate. For example, the poorly graded sand shown actually includes a number of similar soil types. While such might have been acceptable to a contractor planning load and haul operations, the lack of detail involved would probably be less than acceptable to a structural engineer. Likewise, much of the data normally included in the soil column drawings (moisture content, for example) was not included because of resulting data clutter.

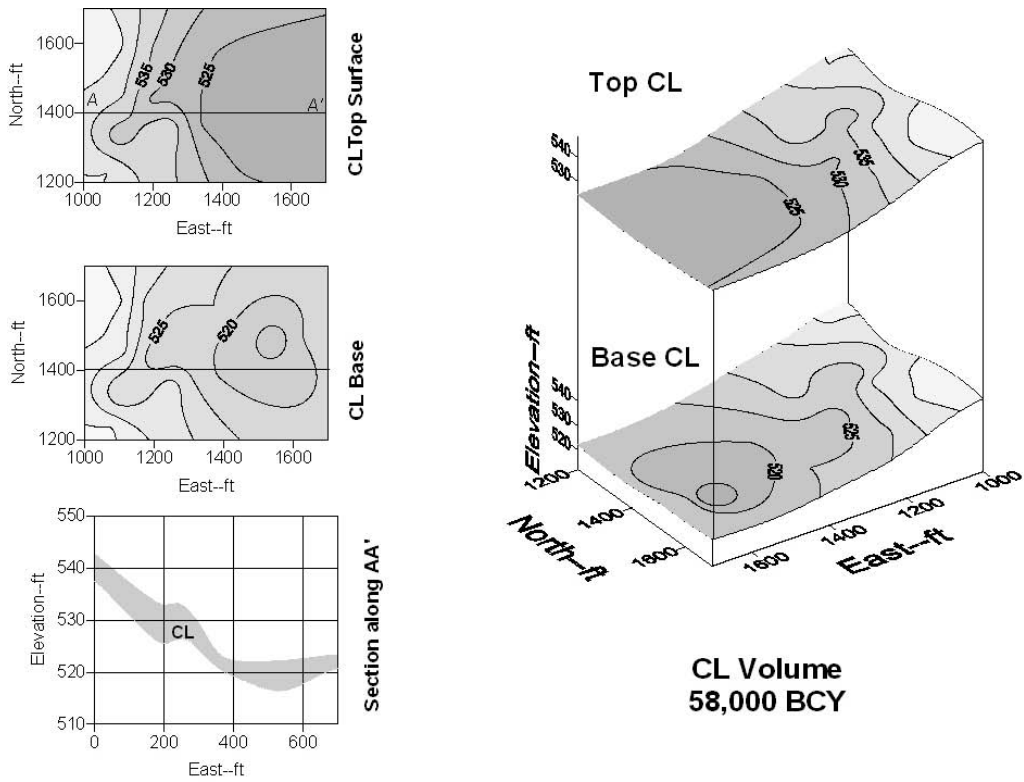


Figure 4. Intersurface detail.

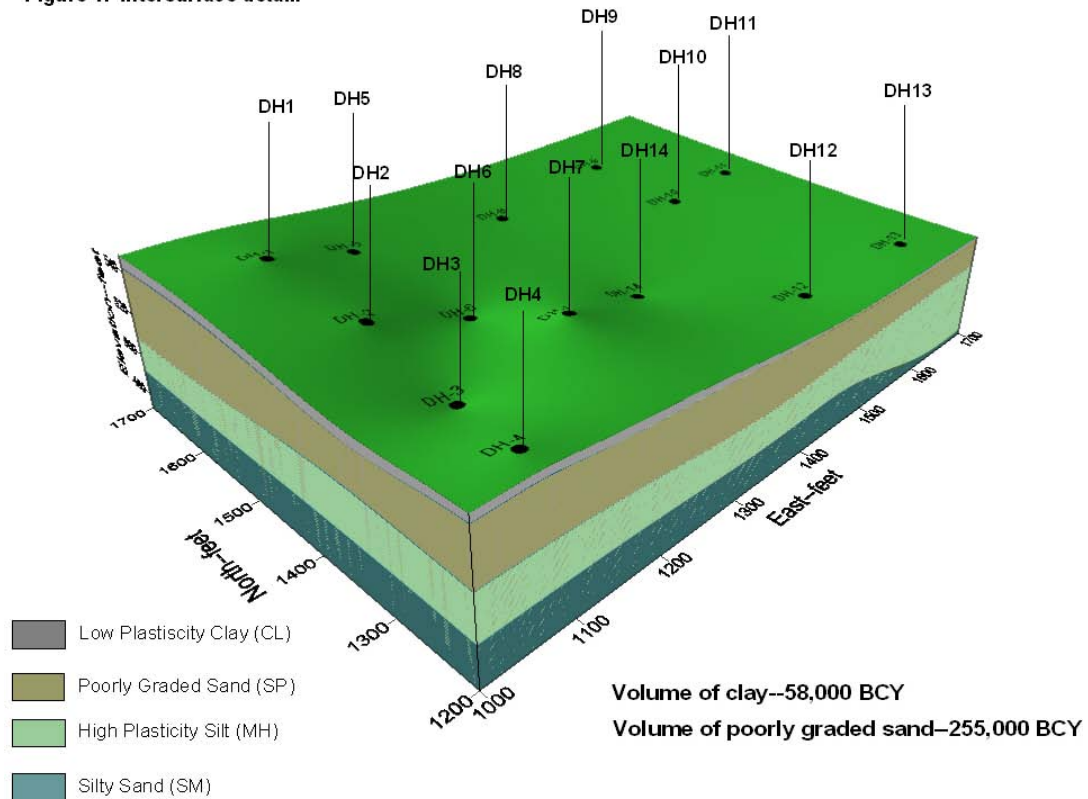


Figure 5. Block diagram based on drilling data, study area 3.

**Volumetric computations.** Volumetric computation were based on grids generated by use of a triangulated irregular network (TIN), by Kriging, and by the method of minimum curvature. Each volume computation by Surfer computes cut and fill volumes by use of the trapezoidal, Simpson's, and Simpson's 3/8 rules using equations (2) through (7) above. In general, the three values converge as grid size decreases.

However, it must be noted that when small data sets are used to define the area mapped, each gridding method will define the surface differently based on the assumptions made with the specific gridding algorithm as noted above. This results in markedly different volume estimates when different gridding algorithms are used with sparse data. The differences that resulted in this research are shown in table 1.

| Figure | Kriging | Minimum Curvature | TIN    |
|--------|---------|-------------------|--------|
| 1      | 24,096  | 20,475            | 23,643 |
| 2 (SC) | 55,499  | 55,314            | 42,122 |
| 2 (GW) | 115,866 | 108,973           | 82,848 |
| 5 (CL) | 58,038  | 56,457            | 36,113 |
| 5 (SP) | 254,723 | 271,232           | NA     |

Table 1. Volumes in bank cubic yards for figures and materials as computed through data gridded using the Kriging, minimum curvature, and triangulated irregular network gridding algorithms.

## Conclusions

The work done to date with three dimensional mapping investigated multiple different methods for the portrayal of these data. Based on this work, we can draw the following conclusions:

1. A block diagram (figures 3 and 5) appears to be the most effective of the methods investigated for showing three dimensional structure. The block diagram has the limitation, however, of not clearly showing intersurface drillhole location. This situation would be remedied by using semi-transparent surface models.
2. Separated surfaces (figures 1, 2, and 4), a technique new to the investigators, provided a good deal more information than had been anticipated. In particular, this type of drawing clearly illustrated the shape of the bounding surfaces, and the use of a section drawings further clarified material distribution.
3. Various color and pattern selections were tried before settling on the color schemes shown, but more work is necessary in this area. We operated on the premise that persons using the drawings would be cued to content by color selection. For example, a gray was used for clay, yellow for sand, and brown for gravel. However, persons who are color blind do not benefit from such cues, and use of standard patterns would appear to be an alternative. Obviously, standard patterns and color schemes are still to be developed/

4. Obviously, different gridding methods yielded different volumetric computations. However, one must recognize first that the data on which the gridding was based was very sparse and second, that the data were not obtained at breakpoints in the surface being mapped. Based on our experience with data sets used to map surface topography, the authors would routinely select the method of Kriging. However, this judgment is based on breakpoint data and denser data sets.

In conclusion, the use of three dimensional drawings as a method of presenting geotechnical data has the advantage of better visualization than is typical of two dimensional drawings. While the quality of volume estimates certainly reflects data processing techniques, volume estimates reflect even more the extent of drilling or other subsurface data that form the physical basis for the volume estimate. While color and pattern assist in interpretation, they cannot be considered as alternatives to adequate data necessary to support accurate materials and volume estimates.

### **Acknowledgments**

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The trapezoidal rule uses the relationship

**Appendix A. Equations used in earthwork computation.**

The trapezoidal rule uses the relationship

$$A_i = \frac{\Delta x}{2} [G_{i,1} + 2G_{i,2} + 2G_{i,3} + \dots + 2G_{i,nCol-1} + G_{i,nCol}] \dots\dots\dots(2)$$

from which the volume can be found by

$$V = \frac{\Delta y}{2} [A_1 + 2A_2 + 2A_3 + \dots + 2A_{nCol-1} + A_{nCol}] \dots\dots\dots(3)$$

where  $A_i$  = area under the function along line  $i$ ;  $G_i$  = depth of cut or fill;  $\Delta x$  = spacing between depth measurements;  $V$  = volume; and  $\Delta y$  = spacing between profiles (Surfer, 2002).

Simpson’s 1/3 rule can be stated as

$$A_i = \frac{\Delta x}{3} [(G_{i,1} + 4G_{i,2} + 2G_{i,3} + 4G_{i,4} + \dots + 2G_{i,nCol-1} + G_{i,nCol})] \dots\dots\dots(4)$$

from which the volume can be found from

$$V = \frac{\Delta y}{3} [A_1 + 4A_2 + 2A_3 + 4A_4 + \dots + 2A_{nCol-1} + A_{nCol}] \text{ (Surfer, 2002)} \dots\dots\dots(5)$$

Simpson’s 3/8 rule uses the relationship

$$A_i = \frac{3\Delta x}{8} [G_{i,1} + 3G_{i,2} + 3G_{i,3} + 2G_{i,4} + \dots + 2G_{i,nCol-1} + G_{i,nCol}] \dots\dots\dots(6)$$

from which the volume can be found from

$$V = \frac{3\Delta y}{8} [A_1 + 3A_2 + 3A_3 + 2A_4 + \dots + 2A_{nCol-1} + A_{nCol}] \text{ (Surfer, 2002)} \dots\dots\dots(7)$$