Clay, gravel, loam, silt, topsoil, organics, miscellaneous material and unsuitable fill; in a word: dirt. No matter what type it is or what you call it, if you own it, design it or move it, you want to know how much of it there is. Enter the practice of calculating earthwork quantity takeoffs. Of all the materials and procedures that go into a land development project, earthwork quantity takeoff estimates often provoke perhaps the most discussion among surveyors, engineers, contractors and other land developers. One reason for discussion, and perhaps the most important, is cost. Moving dirt onsite is expensive, but importing or exporting excavated material to or from an offsite location is even more costly. It is critical to get an accurate estimate of the quantity of dirt to be moved and whether the earthwork cut and fill volumes balance. This need for accurate estimates leads to further discussion as to how earthwork quantities can be estimated.

Who’s Doing the Calculations?
Whether done by the design engineer or the earthwork contractor, earthwork quantity takeoff estimates are a paramount part of the land developing process. They are used to minimize earthwork movements; balance import and export transitions by equalizing cut and fill processes; estimate probable costs for bonding, bidding and project cost planning; and identify possible errors in the earthwork quantity takeoff estimates prepared by others. The process of creating accurate quantity earthwork takeoffs (along with the related software) is gaining in importance as greater numbers of earthwork contractors use GPS-guided machines that require accurate surface models for their mass grading operations.

How are the Calculations Done?
The basic process of determining earthwork quantity takeoff estimates is the same for the design consultant and the earthwork contractor:

• Create a digital 3D model* of the existing surface, accounting for stripping of topsoil or other non-structural material.
• Create a digital 3D model of the proposed surface, accounting for the placement of finish materials such as pavement.
• Calculate the volume difference between the existing and proposed surfaces.
• Generate reports or cut-and-fill maps.

*Figure 1. The various data types available to define a surface in Autodesk Civil 3D.

The ins and outs of moving dirt by estimating earthwork quantity takeoffs.
Gone are the days of hand-drawn estimates. Today, many different software packages are available for creating existing and proposed TINs (digital models) and calculating the volume difference between them. Most programs also provide tools for generating earthwork quantity takeoff volume reports. The programs’ features and capabilities can vary widely based on price and the intended purpose of the software (i.e., a civil engineering design suite versus a dedicated earthwork quantity takeoff program).

Generally, earthwork software can be divided into two categories: comprehensive design and analysis software (design software), and task-specific software. For example, Land Desktop 2005 and Civil 3D 2005, both from Autodesk (www.autodesk.com) provide a comprehensive design solution for engineers and surveyors for all aspects of a project including tools for earthwork volume quantity takeoff estimates. Task-specific software, on the other hand, is intended for earthwork operations, including creation of TINs, earthwork quantity takeoff estimates and coordination with machine control hardware and software. While this latter group of programs lacks the breadth of functionality of the design software, the feature set for performing earthwork quantity takeoff estimates is typically more expansive and clearly focused. Impressive examples of these task-specific programs are Earthwork 3D from AGTEK (www.agtek.com) and Takeoff 2004 from Carlson Software (www.carlsonsw.com). They have features not usually found in design software, such as advanced functions for converting two-dimensional design files (paper or digital CAD) into 3D surface models. In fact, many of these task-specific applications have evolved beyond tools used for estimating and now function primarily to create highly accurate 3D surface models for use in GPS-guided machine control grading operations.

**Existing TIN Creation**

The first step in estimating the earthwork volumes is for the surveyor or design consultant to create a digital model of the existing ground (EG) to which a proposed surface TIN will be compared. The EG usually includes definition of topsoil strip regions and other areas of interest. Typically, engineering and surveying consultants create the EG using field-observed survey data. Contractors usually work from plans (paper or digital) prepared by the consultants. A surveyor's field data (coordinates, point annotations, etc.) are usually contained in a data collector file which can be downloaded to create a TIN.

This data is combined with other information such as breaklines, faults, slope lines and CAD entities to create a model of the existing ground. (For additional information regarding the TIN creation process, refer to “The Making of a Model,” p. 14, *Site Prep*, Fall 2004.) Figure 1 on page 24 shows the various data types available to define a surface in Autodesk Civil 3D. The EG surface may contain additional information such as contours and general annotation, but these are not essential for earthwork quantity estimates.

If field data is not available, the consultant may elect to form the EG surface by using other sources such as digitized contours from paper plans, 3D vector entities from raster (scanned) contour maps or 3D models created from 2D CAD files. In many ways, these procedures are identical to what
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Figure 4. The Topcon 3D-Office menu used for opening an AutoCAD file.

Figure 5. SiteWork from InSite Software provides a tool it calls “paperless take-off,” which allows users to create surfaces from 2D or 3D CAD files.

the earthwork contractor must do. However, the tools included with most design software applications are much less adept at performing these tasks than those found in task-specific programs.

The earthwork contractor must also create a model of the existing ground. But, he works from a combination of CAD files and paper plans provided to him. The earthwork contractor’s software toolbox includes features dedicated to handling this task. The most common method of turning paper plans into a 3D surface model is by digitizing, which may be supported by either design or task-specific software. Digitizing creates a digital model by tracing linework from paper plans. Figure 2 on page 25 shows the control panel as seen in both AGTEK’s Earthwork 3D and Carlson’s Takeoff 2004. Figure 3 on page 25 shows the Earthwork 3D screen during the digitizing process.

Some applications have features that ease the burden of manually keying in information, such as performing automatic incrementing (or decrementing) of contour elevations as consecutive contours are digitized.

Surface models can also be created by converting two-dimensional drawing entities such as contour lines in CAD files into 3D data. Most applications support CAD file import and offer some conversion tools to prepare the data for use in TIN creation. One of the most common file formats is the Autodesk DWG format. Figure 4 above shows the Topcon (www.topcon.com) 3D-Office menu used for opening an AutoCAD file.

In addition to these semi-automatic conversion tools, alternate methods offer greater automation. Advanced features in some products automate the process of CAD file conversion by recognizing CAD text annotation (e.g., a contour label) and assigning an elevation to the CAD entity. TakeOff 2004 from Carlson offers a broad set of automation tools for conversion of CAD files. Functions such as automatic assignment of elevations to contours and other entities are offered.

SiteWork from InSite Software (www.insitesoftware.com) has a tool called “paperless take-off,” which allows users to create surfaces from 2D or 3D CAD files. If the entities do not have the correct elevations, they can be easily assigned at the time the objects are imported from CAD. (See Figure 5 above right.)

The EG surface model represents the ground as it existed when it was surveyed. However, it is common practice to strip topsoil and other nonstructural material from a site prior to commencing mass earthwork operations. This stripped material is stockpiled, and the volume is calculated separately from the mass earthwork volumes. To accurately prepare earthwork quantity estimates the EG model must account for these stripped regions. In general, design software does not provide a straightforward method (compared to task-specific software) to create and modify stripping regions. Typical design software provides tools for editing a surface, including raising and lowering the entire model as well as the ability to create multiple regions of varying depths. The Soil Boring Model feature of Eagle Point 2004 (www.eaglepoint.com) allows the user to manage subsurface models that are parallel or absolute to another surface model. The stripped surface automatically appears as a separate surface in the Surface Manager Model.

Similar results can be obtained in Autodesk Land Desktop 2005 by building a terrain surface using points with the various topsoil depths and then generating a composite of this surface and the EG. In both programs, the end result is a model of the EG stripped of surface materials.

While design software supplies an adequate set of tools for creating strip regions, task-specific software typically excels at it. Each strip region is assigned a depth of the material to be removed. In the earthwork quantity takeoff calculations, the software accounts for these areas and tracks their volumes as a separate quantity.

One example of this is a feature in Trimble’s (www.trimble.com) Paydirt called “Subgrade Adjustments,” which is used to account for stripping surface materials. Areas to be stripped are defined as Areas of Interest and then copied to a subgrade adjustment. Figure 6 on page 27 shows the feature.

After the EG surface has been created and all necessary surface materials have been stripped or otherwise accounted for, the next step is to create a model of the proposed surface.
**Proposed TIN Creation**

The engineer begins with a preliminary design and preliminary earthwork quantity takeoff estimate. Working from this a "pre-final" grading design and earthwork quantity takeoff estimate is developed. At this point, more thorough estimates are prepared, dividing the calculations into different materials, such as topsoil, clay and also accounting for finish materials such as paving asphalt. Using features of the design software, the engineer can create proposed roadway surfaces, building pads, detention basins and other pertinent grading design elements, and combine them to form the proposed surface TINs.

Most design software is capable of creating proposed finished (top) surfaces. Autodesk Civil 3D includes a powerful corridor modeling tool that allows users to quickly and easily create and compare various surface designs.

Combining these grading design elements with others such as grading objects, points and basic CAD entities, a complete proposed surface model can be created. The tricky part to accurate earthwork estimates is modeling the subgrade (or mass earthwork) surface. As when creating the EG surface, design software has limited tools for adding surface materials such as topsoil respread or residential homesites with stepped mass earthwork designs. At the pre-final design stage, the level of detail of the proposed subgrade surface is sufficient to refine the volume calculations and then make adjustments to the site design as needed. For example, the pre-

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final estimates may indicate an excess of clay material and, therefore the engineer may elect to modify the design to either reduce cuts or increase fill requirements to create a balanced site. After making such changes, the engineer expects to have a grading design that results in a balance of the clay cut to fill. Finally, from the final grading design, the finished and subgrade surface TINs are created with enough detail to represent how the surface will actually be built. These TINs, in conjunction with the EG TIN, are used to generate the designer’s most accurate earthwork quantity takeoff estimates.

The engineer uses an iterative process to develop a final grading design, proposed surface TINs, construction documents and earthwork quantity takeoff estimates; the earthwork contractor, on the other hand, has a straightforward approach to generate similar results. The earthwork contractor’s process for creating proposed TINs is similar to his process for creating the EG TIN. However, like the engineer, the contractor’s task of creating these proposed TINs is more complicated than creating the EG, due to the more complex nature of the proposed subgrade surfaces. Fortunately for the earthwork contractor, the task-specific applications commonly used in the construction industry have a well-developed set of features for this purpose. Many of these tools are extensions of the concepts used to create stripping regions on the EG. Proposed contours alone do not usually convey enough detail for construction; spot elevations are also used. Additionally, proposed subgrade surfaces are not always shown in plan view, but rather their construction details are shown on cross-sectional details as shown in Figure 7 on the left.

Just as when creating EG surfaces, there are a variety of methods by which the proposed surface TINs can be generated. These include digitizing and importing CAD entities such as contours and curbs in different layers. The applications can convert plain text annotations into elevation values and assign them to the design elements at the correct locations. For example, a three-step feature in Carlson’s TakeOff 2004 provides a means to convert two-dimensional polylines and simple text annotation into 3D polylines that can then be used in creating a proposed surface model. Applications from InSite Software and AGTEK have features that are similar in function but vary in execution and power.

Upon creation of the proposed finished surface, areas of interest boundaries are defined and depth of materials entered. A powerful feature in some of these applications is the ability to track finish material quantities or estimates for pavement, granular subbase, curb and gutter, etc. Some programs even accept the entry of unit costs for these items, making the tasks of overall bid process and project cost estimates easier.

At this point in the process, the designer and contractor have created models of the surfaces to be compared and from which volume estimates will be determined. The next step is to perform the calculations.

**Calculate Earthwork Quantity**

The work up to this point has been to prepare for the quantity volume calculations, which can only be as accurate as the surface models. Next, the limits of earthwork must be defined. In many instances, grading operations may extend across the entire site, but various internal areas will be left untouched (e.g. wetlands or stands of trees). Defining these limits is critical to obtaining useful results.

There are a variety of methods for calculating the volume difference between two surfaces, some more accurate than others. These methods include the Grid Method, the Average End Area Method, the Prismoidal Method and the Composite (or TIN) Method.

In the Grid Method, the area of interest is overlaid with a grid and the difference between the EG and proposed surface

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**Figure 7. Subgrade (mass-grade) surface shown in cross-section.**

**Figure 8. Eagle Point 2004 “Calculate Prismoidal Volumes” dialog.**

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Elevations are calculated at each corner of each grid cell. The four values are then averaged and then multiplied by the cell area to determine a volume difference for each cell; the sum of these is the overall site volume. InSite Sitework uses this method.

The Average End Area Method uses evenly spaced parallel cross-sections cut through the site to determine volume differences. At each cross-section, the area bounded by the proposed and existing surfaces is calculated. This area is then averaged with the area calculated for the adjacent section and multiplied by the distance between the sections. The sum of these calculations is the total site volume. Most applications offer this as a calculation option.

A more accurate method, the Prismoidal Method uses a form of finite element analysis to calculate volumes. Each side of the triangles representing the proposed surface TIN is projected onto the existing ground surface TIN. The points where the TIN lines from each surface intersect are then projected back onto the triangles to define a subarea on each tri-

angle. These subareas are then averaged and multiplied by the distance between the centroid of the subareas to yield volumes; they are then summed to get total site volume. Eagle Point 2004 uses this method.

The Composite Method, also referred to as the TIN method, is the most accurate method for determining earth
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volume between two surface models. This method creates a new triangulated surface based on points from both the existing and proposed surfaces. It determines where a triangle edge or point from the proposed surface crosses an edge or point from the existing surface and calculates the elevation difference at these locations. This data is then used to create the new TIN. Autodesk Land Desktop 2005 uses this method.

Typically, when the “calculate volume” command is selected the user has the option to enter shrinkage and expansion factors to be used in the volume calculations. These factors attempt to account for shrinkage and expansion of the earth being moved. Figure 8 on page 28 shows the Eagle Point 2004 Calculate Prismoidal Volumes dialog.

After the volume calculations are complete, the total cut and fill volumes are reported on screen. If the site is not balanced, the experienced engineer or estimator can usually determine what modifications to the design are needed to create a balance. However, this can be time-consuming and only somewhat accurate. Many applications provide assistance in this area by automatically adjusting the proposed surface (within user-defined parameters) to create an earthwork volume balance.

Reports and Plots

The final step in earthwork quantity takeoff estimates is the generation of summary reports and cut/fill plots. Summary reports compile all computed information about the earthwork computations. These volumes can be further subdivided into cut-and-fill for various regions of the site, such as open space areas that do not need structural fill and roadways that do. Different material types can be grouped together to make cost estimating easier. Locations of cut-and-fill can be determined by region name to assist in construction sequencing. Figure 9 on page 29 shows a sample volume report from AGTEK Earthwork 3D.

While these reports are useful, the information contained within them often needs to be further manipulated. For example, unit costs need to be assigned so that an estimate of costs or a bid can be prepared. This type of work is typically done in a spreadsheet and most software used for earthwork quantity takeoff estimates can export to Excel and other general file formats such as ASCII and CSV.

In addition to text and numbers, visual representations of the site and the work to be done are another valuable tool in analyzing the results of the earthwork computations. A common form of output is a cut-and-fill map. These color-coded maps show the areas of cut and fill and can be formatted in a variety of ways. Figure 10 on the left shows a cut-and-fill map. The areas of cut are shown in shades of red and the areas of fill are shown in blue. Also shown on the map is a grid indicating the depth of cut or fill at that location.

Sophisticated Software for Professional Use

Earthwork quantity take-off estimates are a critical component of nearly all land development projects. Both designers and excavators must prepare these important calculations to ensure sound design, constructability and cost-effectiveness. Several potent software applications have been designed to make the process of earthwork quantity take-off estimates efficient and accurate. Using these sophisticated tools, engineers are designing projects that satisfy design requirements while economically minimizing earth movement. Contractors are using similar applications to accurately bid jobs and prepare terrain models for use in GPS-guided machine control grading operations. Preparing earthwork quantity takeoff estimates can be a complicated task. Fortunately, the strength and versatility of the current crop of estimating and modeling software makes the task easier and increases user productivity. However, the results output will only be as good as the information entered; therefore it is critical that the software is used by professionals who have a solid understanding of the modeling and estimating process and who fully understand the many features of these powerful software tools. SP

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*Note: Many different terms are used for digital surface models including digital terrain models (DTMs) and triangulated irregular networks (TINs, TNETS, Tri-Nets). Although there are technical differences, for simplicity, this article will make use of the term TIN when referring to digital surface models.

For a more comprehensive explanation of quantity takeoff software, click to www.siteprepmag.com for the complete version of this article.