Earthwork Data Procurement by Photogrammetric Methods

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Considerable interest has been shown in the use of photogrammetric methods for obtaining cross-sections and other forms of terrain data for the determination of earthwork quantities. This paper outlines some of the current and proposed methods and discusses the various factors involved. The relationship of the electronic computer and other instrumentation devices to the method of obtaining and processing the data is discussed. A summary is given of the current research activity by the M. I. T. Photogrammetry Laboratory related to earthwork data procurement.

●DURING THE PAST several years, there has been a tremendous increase in interest in photogrammetry as applied to highway engineering. This activity has been stimulated largely by the efforts of the Bureau of Public Roads to increase highway engineering productivity throughout the nation. Photogrammetry and electronic computers have received the principal emphasis in this program of encouraging highway organizations to take full advantage of the developments in modern technology.

The rapid rate of development of photogrammetric and electronic computer techniques is having considerable impact on highway engineering theory and practice. Acceptance and utilization of new methods ranges from enthusiasm to refusal. The variations in opinions and policies toward such subjects as the acceptance of photogrammetric data and the need for plotted cross-sections are well known. A review of the subject shows that there is good reason for such variations. The first part of this paper is devoted to a discussion of some of the basic factors involved in terrain data requirements for highway engineering which are at the root of many differences of opinion.

The second part of this paper is devoted to a discussion of some of the photogrammetric methods of obtaining earthwork data and the factors which must be considered. The balance of the paper is devoted to a discussion of some of the research developments of the Photogrammetry Laboratory of the M. I. T. Department of Civil Engineering which are being conducted under the sponsorship of the Massachusetts Department of Public Works in cooperation with the Bureau of Public Roads.

TERRAIN DATA FOR HIGHWAY ENGINEERING

Uses for Terrain Data

A representation of the surface of the terrain or topography of the area of interest is utilized as a source of data for each of the following aspects of highway engineering:

1. Analysis and selection of the location of the highway;
2. Computation of earthwork quantities;
3. Design of the highway and related features; and
4. Construction of the highway and related features.

The above are four separate and often distinct uses for terrain data and each use involves a different set of data requirements. The differing requirements are often overlooked in debating new methods and approaches. Heretofore, the same cross-sections adequately served for earthwork quantities, design and construction. However, it is now apparent that the differing requirements must be recognized in order to realize the greatest value from photogrammetry and electronic computers.

Form of Terrain Data Presentation

Terrain data may be presented in the following basic forms:

1. Graphical or analog form. Such data is usually in the form of continuous lines on a graphical plot. The contour map and the continuous line profile are examples of an analog form of presentation of terrain data.
2. Numerical or digital form. In contrast to the continuous line characteristic of analog data, digital data is composed of a number of discrete points with associated numbers. Tabulated cross-section data or a series of x, y, z coordinates are examples of digital data. Data recorded on punched cards or tape is in digital form.

For visualization and utilization by the human mind, data must usually be presented in analog form. The contour map and the plotted continuous line cross-section are the forms of terrain data presentation for the engineer. They also represent the form of data required when an analog computer such as a planimeter is to be used in conjunction with the data.

When the terrain data is to be utilized for numerical computational purposes such as input data for a desk calculator or electronic digital computer, it must be presented in a digital form acceptable by the computing machine. The distinction of analog form for human utilization and digital form for machine utilization is basic to a better understanding of data problems associated with new approaches to highway engineering. Heretofore, the same data has often adequately served for both the engineer and computational purposes. However, with the use of electronic computers, a distinction must be made between the forms of data presentation for the engineer and for the computer. The use of electronic computers by no means eliminates the need for an analog presentation for the benefit of the human engineer.

The fact that plotted cross-sections are not required for the computation of earthwork quantities does not necessarily mean that they can be eliminated from the scene. It does mean that the requirements for plotted cross-sections are now dictated by their use by the designer and constructor instead of the computational procedure for earthwork quantities. Recognition of this factor has been largely overlooked in the current debate over the need for plotted cross-sections. In conclusion, it may be stated that the form of terrain data presentation is a function of the intended use of the data.

Accuracy of Terrain Data

With regard to the accuracy of terrain data, it is important to recognize the following:

1. Terrain representation systems such as contour lines, spot elevations, profiles, and cross-sections are approximations to the true surface of the terrain in that they represent a sampling of the infinite number of lines or points which would be necessary to represent the complete surface.
2. A distinction should be made between point accuracy and statistical accuracy. By point accuracy is meant the absolute error (difference between represented surface and true surface) at a discrete point. By statistical accuracy is meant the mean error considering a large number of points representing an area of the surface. If the point errors are random in nature (equal chance for positive and negative errors, large number of small errors, small number of large errors), the mean error considering a large number of points will approach zero. Hence it is possible to have poor point accuracy and excellent statistical accuracy.

The accuracy of representation or degree of approximation is largely a function of the density of contour lines or points used to represent the terrain and the terrain slope characteristics and basically influence our choice of contour interval or point spacing. It is obvious that the intended use of the terrain representation will influence the degree of approximation which will be permitted. The intended use will also dictate whether point accuracy and/or statistical accuracy is needed. In earthwork volume computations, since a rather large number of points is being used, it is apparent that the requirement is often for point accuracy. In many design cases, the point accuracy requirement is such that the data may be presented in analog form such as a large scale plot of a cross-section. In some cases, the analog form must be supplemented by digital data at selected points such as recorded distances and elevations.

Sources of Terrain Data

For the purposes of representation, the terrain may be measured directly at full scale (field survey) or indirectly at reduced scale in terms of a model (photogrammetry). The data resulting from the field survey is digital in form. It may be retained and utilized in the digital form or it may be plotted and presented in analog form. The data resulting from measuring the photogrammetric model may be directly recorded in analog form or it may be recorded in digital form.

The graphical plot resulting from either source may be converted back to digital form but normally with some loss of accuracy over the original data in the case of the field survey and the possible direct digital data in the the case of the photogrammetric source. Essentially, it must be realized that data scaled from a map cannot be expected to have the same accuracy as the data used to compile the map. However, the map does serve as a very convenient medium for storing large quantities of terrain data for later recovery.

The sources of numerical terrain data may be summarized as follows:

1. Directly from the field survey recorded in digital form;
2. Indirectly from the field survey recorded in analog form;
3. Directly from the photogrammetric survey recorded in digital form; and
4. Indirectly from the photogrammetric survey recorded in analog form.

Source 1 is "capable" of furnishing the highest point accuracy. Since source 4 can usually furnish equivalent accuracy to source 2 at less cost, source 2 is of diminishing practical importance. Source 4 is "capable" of furnishing relatively good statistical accuracy for many purposes and sufficient point accuracy for some purposes. Source 3 is "capable" of furnishing better point and statistical accuracy than source 4 and better statistical accuracy than source 1 on the basis of economical comparison. The choice of data source is basically a function of intended use which in turn dictates form of presentation and accuracy required.

Terrain Data for Highway Location

For the study of a highway location problem by the engineer, the topographic map is of course the standard tool. A contour interval such as five feet usually furnishes a sufficient degree of terrain approximation and statistical accuracy, and the use of photogrammetry is well established. Possible new approaches to highway location utilizing electronic computers do not at the present time involve any change in the requirements and utilization of the location map by the engineer. The electronic computer will require its own set of terrain data when utilized to make numerical evaluations in the location phase in addition to the map as the engineer's form of data presentation.

Terrain Data for Earthwork Quantities

The basic requirements for terrain data for earthwork volume computations are as follows:

1. A degree of terrain approximation and statistical accuracy consistent with the earthwork accuracy requirement, and
2. A digital form of data presentation.

The earthwork accuracy requirement is a function of the intended use of the resulting volumes such as (a) preliminary quantities for use in comparing alternate routes and selecting the preliminary location, (b) preliminary quantities for estimating purposes, (c) final quantities for use in selecting the final alignment from possible variations from the preliminary location, (d) final quantities for estimating and bidding purposes, (e) final quantities for payment purposes. A data source and method of processing the data must be selected to be consistent with the intended use of the earthwork volumes.

For preliminary quantities, a 5- or 2-ft contour map will often be a suitable data source. For final quantities, a 2-ft contour map may suffice under certain conditions and direct digital data from the photogrammetric model will be adequate under most conditions. Occasionally direct digital data from a field survey will be necessary.

It is important to note that the requirement is for a large number of points with good statistical accuracy rather than a few points with good point accuracy. Statistical accuracy is only achieved if the point errors are random. A small systematic error can result in a large earthwork volume error.

The additional requirement that the data be in digital form adds an additional distinction between terrain data for earthwork quantities and the terrain data for other purposes.

Terrain Data for Design and Construction

The rather obvious but basic observation may be made that terrain data for design purposes is required wherever the engineer is called upon to exercise his design function. A better statement might be that the designer requires special terrain data wherever there is a departure from a standardized design in order to meet the special condition at hand. This means that a basic set of terrain data is required to delineate the sections of standard design and the sections of special design. A contour map will usually furnish sufficient data to delineate such sections and often will serve as an adequate source for the special terrain data for the special design. Drainage design and special slope treatment are examples of design problems for which the map might furnish adequate terrain data.

It is important to note that the map is a convenient and efficient source of data "on demand" whenever the designer needs special terrain data. Hence, it may be concluded that the large scale topographic map will continue to be an important tool of the designer and will not be eliminated by possible use of an electronic computer for quantity determination.

In some cases, the analog presentation of terrain data in the form of a map will not offer sufficient point accuracy for special design problems. In such cases, direct digital data from the photogrammetric model or field survey may be required. However, for visualization by the human engineer, such data will still be presented in analog form in addition to being available in digital form for design calculations.

The requirements for terrain data for design may be summarized as follows:

1. A representation of the terrain of the entire area of interest in analog form with sufficient degree of approximation and point accuracy to delineate sections of standard design and special design; and
2. A representation of the terrain in the sections of special design with sufficient point accuracy to achieve the special design and presented in analog form supplemented with digital data where necessary.

The requirements for terrain data for construction purposes may be simply stated as:

1. Sufficient information to convey the design, both standard and special, to the constructor; and
2. Sufficient information to furnish the constructor with a representation of the existing terrain.

Here again, since the concern is with the human use of the data, it must be presented in analog form supplemented with digital information when accuracy requirements exceed graphical scaling recovery abilities.

PHOTOGRAMMETRIC METHODS OF OBTAINING EARTHWORK DATA

Photogrammetric Map Data

The "stripping" of profile and cross-section data from a contour map is well known. Such methods have long been used for reconnaissance and preliminary estimates of earthwork and lately some agencies have used large scale and small contour interval photogrammetric maps for final quantities. Since the accuracy requirement for earthwork terrain data is statistical accuracy instead of point accuracy, the contour map is capable of furnishing adequate data if systematic errors have largely been eliminated in the preparation of the map. Decreasing the contour interval has the effect of increasing the sample and hence giving a better approximation of the true surface of the terrain. A very carefully prepared two-foot contour map will often be quite satisfactory as a source of terrain data for the computation of final earthwork quantities.

Unfortunately, the widely used tolerance type specification for vertical accuracy (90 percent of the contours correct within one half the contour interval) exercises no control over systematic errors in the map. Therefore, many maps that meet standard map specifications would not be acceptable sources of terrain data for earthwork computations. For example, considering a 2-ft contour interval, if the errors in map "A" are completely random, the expected average point error would be approximately 0.5 ft and the effective point error when 100 such points are used in a calculation would be 0.05 ft and would rapidly approach zero. Map "B" might have a systematic error of 0.9 ft at each point throughout the map, and the effective point error irrespective of how many points were used in the earthwork computation would still be 0.9 ft. Both maps would meet currently used specifications. Map "A" would yield very accurate earthwork quantities and map "B" would yield very erroneous results. Therefore, although the photogrammetric contour map is "capable" of furnishing adequate earthwork data, with currently used map specifications there is no assurance that the map data is adequate. The answer to this problem is to place a restriction on allowable systematic errors in contour maps to be used for earthwork quantities and to independently check each section of the map for compliance with the stated accuracy requirements.

Some of the advantages of the contour map as a source of terrain data for earthwork quantities include:

1. Obtaining cross-section data from the contour map is a very simple process which can be performed by subprofessional personnel and can be achieved with a simple scale as the only instrumentation requirement;
2. The preparation of contour maps is a well established practice with many available sources;
3. The contour map may be prepared in advance, without knowledge of the actual alignment or alignments which are to be considered; and
4. The terrain data is stored in a very convenient form.

Some of the disadvantages of the contour map as a source of terrain data for earthwork quantities are:

1. The accuracy and completeness of the terrain data may not be adequate in many cases, and
2. Taking the data from the map by manual methods is time consuming and subject to human errors and mistakes.

The first disadvantage may be overcome as previously discussed by proper control over the design and preparation of the map for its intended use. The second disadvantage may be partially overcome by adding some degree of automation to taking the data from the map. One of the current research projects of the M.I.T. Photogrammetry

Laboratory is the investigation and development of various instrumentation systems to facilitate the recovery of digital terrain data from contour maps.

Photogrammetric Model Data

A stationary measurement of the photogrammetric model with digital output (point coordinates) can be achieved with greater accuracy than a dynamic or continuous measurement with analog output (contours). Individually read and numerically recorded elevations of single points are usually considered to have twice the point accuracy of elevations of contour lines plotted from the same model. In addition, converting the data directly from the analog model into digital form eliminates the extra analog-to-digital conversion step of taking the data from the contour map. The advantages have led to considerable interest in taking cross-section data directly from the stereoplotter.

A word of caution is in order with regard to the increase in accuracy which may be gained. The increased point accuracy from reading spot elevations is primarily gained from a reduction in the operator's error in placing the "floating mark" in contact with the surface of the ground. This error is largely random except where it is a function of ground visibility. Therefore, reading spot elevations decreases the random error of observation and, using selected points, the possible systematic error due to ground cover or poor visibility. Decreasing the random error contributes little to increased accuracy of earthwork data. Of greater importance is the realization that reading opot elevations does nothing to decrease all other systematic errors in creating the steromodel. For example, an error in model orientation would influence a spot elevation to the same degree it influences a contour elevation.

The accuracy ot spot elevations has also been confused with the least count or smallest increment of the reading. Reading elevations (and distances) to the nearest tenth of a foot with the stereoplotter does not necessarily mean that they are accurate to the nearest tenth of a foot. The average error might well be one-half foot. Therefore, the accuracy of the measurements is not necessarily increased simply by amplifying the reading scales. Amplification is occasionally in order but the smallest reading increment is not to be confused with the accuracy of the reading.

The simplest approach, from the standpoint of instrumentation, for taking cross-section data with a stereoplotter would be to read and manually record spot elevations along graphically plotted section lines. The x and y digital values would then be obtained by scaling the graphical plot. The only instrumentation required would be any standard stereoplotter. The recorded data would be punched on computer input material as a separate and manual step. The simplicity of this approach is quite an advantage and it is already in fairly common use. The principal disadvantage is the manual measuring, recording, and punching steps which are time consuming and subject to human errors and mistakes.

Some interest has been shown in instrumentation for eliminating the manual scaling of the horizontal distances to the cross-section points. As a matter of convenience and increase in efficiency, such a component is justified. However, caution should be exercised in expecting greater accuracy to be realized. If more accurate measuring components have not been used to lay out the manuscript, plot the control, and orient the model to the control, higher order measurements within the model are not justified. Here, again, least reading should not be confused with accuracy. It should be noted that except for the case of terrain slope approaching 45 deg, it is not theoretically necessary to measure the cross-section distances with the same accuracy as the cross-section elevations. This is of course reflected in standard field survey practice.

Mention should be made of the problem of directional scanning. In conventional cross-sectioning practice for earthwork quantities, the offset or horizontal distances are measured at right angles to the centerline or baseline of the highway alignment. In the universal type of plotters, the instrument measuring axes are essentially fixed in direction and cannot be aligned at will in any desired direction. As a result, direct offset distances are not measured and observed with the plotter but rather the two xy components of the desired distance. In addition, the desired cross-section line is not directly observable by the plotter operator so an assistant is required to observe and direct the positioning of the floating mark on the cross-section line as plotted on the manuscript. Various solutions to this problem are being investigated by several groups including the instrument manufacturers. The same problem occurs when a three dimentional scanning unit is placed on a double projection plotter and related to the manuscript via the usual coordinatograph.

Automatic Output Instrumentation

In order to increase the operational efficiency of taking cross-section data directly with the stereoplotter, considerable interest has been shown in automatic instrumentation components for recording the output of the plotter directly on computer input material. The manual measuring, recording, and punching operations can be eliminated if desired by adding an automatic digital readout system to the stereoplotter. Such equipment is now available from several of the universal plotter manufacturers and a number of organizations are developing special systems for use on double projection stereoplotters. Since there are many ways in which the desired results can be accomplished, the various systems differ considerably in detail and technique although functionally they are quite similar. Although there is considerable commercial incentive to claim "the" solution to everyone's requirements and problems, there is still considerable room for new ideas and developments in this field. The future should reveal considerable improvement in flexibility, simplicity and reliability of operation, as well as a reduction in initial cost of such systems. Although the hardware associated with automatic output systems has attracted the most attention, the purpose and utilization of the resulting data is far more important and deserves more thorough study on the part of enthusiasts in this field.

Limitations of Photogrammetric Methods

With the wider acceptance and utilization of photogrammetric methods for obtaining highway terrain data, an understanding of the limitations as well as the applications of the approach is in order. There is great danger in misusing photogrammetric data. Although photogrammetry is capable of furnishing excellent results, unfortunately it is very easy to obtain very poor results. And poor results can be obtained much cheaper than good results.

A photogrammetric system involves a number of steps and instrumentation components each of which offer many sources of error. A complete listing of the sources of error would require many pages. A proper understanding and control over each of these many sources of error is required to obtain adequate results.

The selection and correct use of adequate instrumentation components is of course basic to obtaining desired accuracy. There is considerable variation in the accuracy capabilities of various cameras and stereoplotters, especially when they are not properly calibrated and operated. The dimensional instability of all materials used to temporarily store data while passing through the system is a common source of error. Inadequate or inaccurate ground control and the additional errors contributed by photogrammetric control extension often yield poor results. Model warpage due to careless or inconclusive orientation of the photogrammetric model in the stereoplotter is an extremely dangerous source of error and has accounted for many very poor results. A great deal depends on the skill and experience of the stereoplotter operator and of all the other human elements in the system. Finally, the knowledge and experience of the engineer responsible for selecting and designing the system to be used and responsible for the supervision of the operation of the system is of fundamental importance.

The relatively few thoroughly qualified photogrammetric engineers and skilled photogrammetric technicians is perhaps one of the greatest limitations of photogrammetry in the highway field at the present time. This will be the most serious obstacle to realizing the real potential value of photgrammetry.

Unfortunately, many users of photogrammetric data are responsible for the poor results they often obtain due to the premium placed on price in awarding photogrammetric contracts. Although organizational efficiency and the suitability of available equipment are important factors in cost results, low cost is easily obtained by compromising with accuracy or completeness of data. If price is to be the principal factor in contract award, an extensive independent checking program is essential to insure that adequate accuracy is delivered. A fair fee negotiated in a professional manner with a qualified and reputable organization is the best insurance that good results will be furnished.

A practical limitation of photogrammetry for obtaining earthwork data, one often encountered, is that of ground cover. Accurate and reliable measurements cannot be made when the surface of the terrain is obscured by vegetation or heavy shadows. Under some conditions this limitation can be quite restrictive and photogrammetric methods should not be attempted. However, the same conditions of heavy vegetation can seriously restrict field survey methods by placing a practical limit on the number of points it is economical to obtain. If there are frequent openings in the vegetation from an aerial viewpoint but not from a ground viewpoint, photogrammetry can feasibly obtain more data and thereby better results than a ground survey. However, solid and continuous ground cover even at low height is a limitation which must be respected.

Although speed is one of the principal advantages of photogrammetry over field surveys, the elapsed time between decision and final results can occasionally be in favor of field methods for conventional cross-sections. Although there is no question but what a plotter operator can take cross-sections faster than a field survey party, the plotter operation must await the procurement of suitable photography and ground control. If these phases have not been scheduled in advance, the elapsed calendar time might be in favor of field methods. This is particularly true under terrain and visibility conditions which do not handicap field operations. There are also cases in which it would be cheaper to take the cross-sections by field methods. The authors are by no means attempting to promote field methods but only to point out that photogrammetry cannot be looked upon as applicable to all conditions and cases, but should be used to advantage and not misused to disadvantage.

CONVENTIONAL APPROACHES TO EARTHWORK ANALYSIS

Limitations of Current Approaches

The principal limitation of the current approaches to determining earthwork is that the terrain cross-sections are taken with respect to the horizontal alignment. This presents two problems:

1. The horizontal alignment must be selected and established either on paper or on the ground before the terrain cross-section data can be obtained, and
2. A separate and new set of terrain cross-section data is required for each trial horizontal alignment or changed alignment except for minor lateral shifts.

Scheduling and Coordination Problems

The requirement that the alignment must be given presents a scheduling limitation. The engineering phase must proceed to the point of selecting the line or lines and then must cease, often for a considerable length of time while the cross-section data is being obtained. Even if the data is to be obtained by photogrammetry, considerable time is often required to arrange for a contract, await the proper season and obtain aerial photography, perform and deliver the work, inspect and check the data. If it is required that the line be staked on the ground before the cross-sections are taken, this imposes considerable additional time and scheduling problems in the middle of the engineering phase.

The above scheduling, coordination, and time problems could be reduced if it were possible to obtain all of the data necessary to represent the terrain for earthwork purposes prior to the step of actually selecting and staking the line.

Earthwork as a Location Factor

The second problem of requiring a separate set of cross-sections for each horizontal alignment places a limitation on the number of possible solutions which it is practical to consider. To evaluate ten trial lines or possible solutions would be essentially ten times more work than a single line. Therefore, it is common practice to reduce the number of trial lines to two or three by inspection or map study. Often the final line is selected without the numerical evaluation of any alternates. Earthwork (cuts and fills) are balanced by variations in the vertical alignment or grade line.

It can be said that the conventional approaches to highway location practice with respect to earthwork achieve an acceptable solution but not necessarily the optimum solution. It has heretofore been considered impractical to numerically evaluate a large number of trial solutions due to the engineering time and costs involved, despite the possible savings in the earthwork costs. Two different highway location engineers independently studying the same location problem with respect to earthwork will often arrive at quite different solutions to the problem although both solutions will be good and acceptable. The extent to which either solution approaches the optimum is really not known although each locator is confident that he has the "best" solution.

With respect to the desire for more thorough analysis of highway location with respect to earthwork, the argument is usually raised that earthwork seldom controls the location. It is pointed out that land use and right-of-way cost is often the controlling factor or that the earthwork volume is so small it is not considered a location factor. This is certainly true in many cases and more attention to earthwork is not advocated under such conditions. However, even in such cases, due to the time and cost involved, determining the earthwork even if it is a small amount warrants consideration of more efficient methods of obtaining the data and computing the quantities.

Although the complex and expensive urban highway projects are in the forefront of consideration by many highway engineers, rural locations are still very much in the picture. Depending on the terrain, earthwork may vary from a minor to a major role as a location factor. In many cases, there is ample justification for a more thorough numerical analysis of possible location solutions with respect to earthwork if such analysis can be made within practical reason. Even the most conservative estimates of the amount of money which will be spent on earthwork in accomplishing the national highway program indicated that a relatively small percentage saving in earthwork volume will account for hundreds of millions of dollars.

From the above, it may be concluded that any new approach to the earthwork problem should have the dual mission of:

1. Reducing the engineering time and costs involved in obtaining and processing earthwork data, and
2. Reducing the construction cost by permitting a more thorough analysis of possible location solutions.

Potential for New Approaches

The efficiency of photogrammetry for obtaining terrain data and the efficiency of the electronic digital computer for processing data is generally recognized by the highway engineering profession. These two tools are being used to varying degrees by most all highway organizations. However, the approach so far has been largely one of replacement. The stereoplotter is replacing the survey party for plotting maps and taking cross-sections. The electronic computer is replacing the planimeter and desk calculator for computing areas and volumes. However, the approach to the earthwork problem is largely the same as it has been for decades. The same type of cross-sections are still being taken except now with the stereoplotter. The same type of calculations are still being performed except now with the electronic computer.

It should be recognized that photogrammetry is a very efficient method of obtaining large volumes of terrain data and that the electronic digital computer is a very efficient method of processing large volumes of data. The efficiency of the combined systems offers an opportunity to deviate from the traditional approach to the earthwork problem which is predicated on the practical limitations of essentially manual methods.

Before photogrammetric methods were adopted for highway mapping, the highway location engineer was usually content with a topographic map of a relatively narrow band of several hundred feet in width. When the efficiency of photogrammetric mapping was recognized, the mapping requirement was changed to a band a mile in width in order to do a more thorough job of planning the location. It is expected and advocated that the same extension of thinking take place with respect to numerical analysis of location solutions.

DIGITAL TERRAIN MODEL APPROACH TO EARTHWORK ANALYSIS

The Digital Terrain Model

In order to accomplish the goals which have been presented above, the concept of a digital terrain model has been proposed by the senior author in several earlier papers and reports. By a digital terrain model is meant a statistical representation of the terrain with a system of discrete points with known xyz values. Digital representation of terrain is nothing new to the highway engineer. The map with relief shown by spot elevations and the conventional cross-section are two examples of digital representation by a system of discrete points. The proposed digital terrain model will differ from the above two examples by the following characteristics.

1. The representation is completely in numerical form, meaning that the location (x and y values) as well as the elevation of each point is directly available. (The map with spot elevations can appropriately be termed a digital map but the location of the points is given in analog form.)
2. The points are located in space with respect to a spatial or coordinate reference system which coincides with or is related to a ground recoverable reference system such as the state plane coordinate system. (Ordinary cross-section points are referenced to a given highway alignment.)
3. The storage medium for the digital terrain model is some form of electronic computer input material such as punched tape, punch cards, or magnetic tape.
4. The points are recorded on the computer input material in a sequence or system such that the computer can perform terrain analysis problems according to programmed instructions without the necessity of human interpretation of the terrain for the computer.
5. The digital terrain model in its stored form is usable for an infinite number of independent solutions to terrain analysis problem of the stored area with complete hor izontal and vertical freedom.

The fifth characteristic implies that the single set of stored terrain data could be used numerically to evaluate any chosen horizontal and vertical alignment for a proposed highway within the digitized zone. Such a facility is important to realizing the goals of reducing the amount of work required to consider a large number of trial solutions to a given section of highway. In addition it means that all of the terrain data could be obtained in advance of detailed consideration of the location of the highway alignment.

Digital Representation System

There are a number of possible systems of points to statistically represent the terrain surface. One would be the type of points used by the plane table or transit-stadia topographer where values are determined for terrain control points such as high points, low points, drain lines, and slope breaks. However, such a representation is random in appearance to the computer and the problem of storing, recovering and analyzing the terrain with such points would be quite difficult. The first degree of systematization could be added by taking points only along a system of parallel lines which shall be termed scan lines.

Assuming the scan lines are in the y direction, points may be taken at the following locations:

1. On equal increments of y: if the scan lines are a constant x increment apart, a rectangular grid system would result; if the y increment and x increment are constant and equal, square grid would result. Such a system would probably be suitable for flat or rolling terrain.
2. On equal increments of z: the horizontal density of the resulting points would vary with the terrain slope, with a higher density on the steeper slopes. Such a system would probably be suitable for terrain with a highly irregular surface with frequent slope changes.
3. On increments corresponding to a constant product of yz increments: for example if the constant was given as 20 units, a reading would be taken for such increment combinations of (y, z) as (20, 1), (10, 2), (40, ½), and (5, 4), etc. Here again the density would vary with the slope but such a system would give a better representation than (2) since horizontal as well as vertical changes are considered.
4. On terrain control points along the scan line such as high points, low points, and slope breaks: this system would correspond with the normal cross-section points taken in conventional practice. It would be suitable for all types of terrain and no doubt would be the most acceptable system to the highway engineer until other systems become better known.

The first three systems mentioned above have the advantage that a higher degree of automation could be achieved in the instrumentation for obtaining the data. For example, if the data is being taken with a stereoplotter, the scanning unit could be automatically moved across the model in accordance with the selected equal intervals, relieving the operator of all but one degree of freedom in operating the instrument. In fact, the scanning movement across the model could be continuous and automatic if means are provided for automatically recording the data.

With the above systems the data is taken and stored in a continuous systematic sequence. Therefore, it can be recovered in a relatively simple fashion providing the scan lines are spatially related to a known reference system.

Computer Analysis of the Digital Model

Some of the basic geometric problems which the electronic computer would be called upon to perform on the stored model according to programed intructions would include:

1. Surface elevation of the point corresponding to any given xy value;
2. Coordinates of the intersection of any given line with the surface of the model;
3. Profile values of the intersection of a vertical or random plane with the surface of the model;
4. Line of intersection and area of the quadrature defined by the intersection of a horizontal or random plane with the surface of the model;
5. Volume between the surface of the model and another given surface defined by a series of planes intersecting the model; and
6. Geometric problems such as the above but in which the lines and planes are not given but only their geometric limits and controls.

It is obvious that the surface of the digital terrain model, by definition, is discontinuous. By surface is therefore meant the envelope passing through all of the discrete points of the model. It is apparent that most of the geometric problems listed above involve "interpolated" z values determined by the computer. The accuracy of an interpolated value depends on the agreement between the assumed mathematical surface and the actual surface in the vicinity of the point and hence is a function of the density of the points and the actual terrain characteristics.

Computer Programs

Except for necessary research on the resulting degree of approximation for different types of terrain representation systems and the development and commercial availability of automatic instrumentation, the data procurement phase of the digital terrain model approach poses no real problems. However, the actual use of such an approach will await the availability of the necessary electronic computer programs to analyze the model for basic geometric problems outlined at the beginning of this section and for specific applied problems.

In general, the given lines and planes must be mathematically expressed in the same reference system as the terrain data or to a common reference system such as state plane coordinates. The mathematical relationships for the horizontal and vertical alignment and earthwork volumes for a highway based on simplified geometric controls have been derived and computer programed at the M. I. T. Photogrammetry Laboratory by S. Namyet and R. Laflamme. Related work is continuing on the development of other computer programs to analyze the digital terrain model.

General Applications

The characteristics of the digital terrain model and the interpolation considerations are such that it cannot be expected to yield "exact" values in the civil engineering design sense. It would not be practical to use a high enough density of points to yield interpolated elevations correct within a few tenths of a foot. However, there is a vast range of problems where such accuracy is not required, even in the design stage. In general, it can be said that whenever terrain data is required in graphical form, such as a plotted profile, the data could probably be taken from the digital model.

The major application of the digital terrain model will be to problems involving the determination of quantities such as areas and volumes. In such cases, a relatively large number of terrain points are used. Since the interpolation errors will tend to be random in nature, their effect will tend to compensate and approach zero for a large number of points.

Although this paper is primarily concerned with the digital terrain model for highway earthwork analysis, it should be noted that many of the same concepts and ideas are applicable to such problems as (a) line-of-sight and other terrain clearance problems related to location of communication systems, airport approach zones and military problems, and (b) areas and volumes of reservoirs, open pit mines, stock piles, and other excavation and storage projects. For the latter, the essential reference is to applying the traditional "borrow-pit" computation by a more efficient form of data procurement and processing.

Application to Highway Location

The basic steps involved in applying the digital terrain model approach to the numerical evaluation of the earthwork on many trial solutions may be summarized as follows:

1. Based on a route location study, the band of terrain to be digitized is selected.
2. A set of reference axes is selected for each long dimension of the band. These are designated the skew coordinate axes. The skew coordinate axes are mathematically related to the state plane coordinate system which serves as the basic spatial reference framework for relating all subsequent values to the physical ground.
3. Terrain data is obtained by taking cross-sections perpendicular to the x axis of the skew coordinate system. Such lines in the y direction are termed scan lines. The data may be taken from an available topographic map or may be taken directly with the stereoplotter with automatic digital output. In any event, the data is stored on computer input material in a systematic fashion so that it may be easily recovered.
4. The highway engineer selects as many trial alignments as he may desire to evaluate, furnishing limited input data to define each line horizontally.
5. A computer program furnishes the existing terrain profile data for each alignment.

6. The highway engineer selects one or more grade lines for each trial alignment and furnishes limited input data to define each trial vertically.

7. A computer program furnishes the earthwork data for each trial solution.

8. Based on the first runs, the highway engineer modifies the input data and reruns the apparent best solution until it is optimized.

Each of these basic steps will now be discussed in more detail.

Selection of the Band

The selection of the band to be digitized is basically a matter of delineating the limits within which the optimum location of the highway would appear to be, based on general highway location factors. In the case of a rural location, the location study goes through successive stages of narrowing these limits until they converge on a specific line.

The three basic stages of location which are usually recognized are (a) reconnaissance study (b) preliminary location, and (c) final location. It is apparent that the skew system can be applied to each of these different stages. Therefore, the particular stage being considered will be a basic factor in selecting the limits of the band to be digitized.

In conventional practice, a progressively larger scale, smaller contour interval topographic map is used in location studies as the project passes through the three stages. During each stage, the location analysis with respect to earthwork is primarily a matter of visual inspection of the maps. Two or perhaps three (rarely more) lines are plotted and numerically evaluated. The skew system would permit the numerical evaluation of a much larger number of trial lines but would not materially change the other aspects of location analysis.

Typical mapping requirements for the three basic location stages are:

Stage	Scale	C.I.	Band Width
Reconnaissance	1 in. = 2,000 ft	20 ft	20,000 ft
Preliminary	1 in. = 200 ft	5 ft	5,000 ft
Final	1 in. = 100 ft	2 ft	2,000 ft

Normally it will not be necessary to digitize a band as wide as the standard mapping limits. Visual analysis of the terrain will normally reduce the above limits by a factor of ½ to ¼. Whereas in the mapping case, once a band has been selected, the total area is mapped irrespective of location obstacles, in the digital model case, data would be taken only where a highway location was feasible.

In urban areas, the location is usually dictated almost entirely by land use and traffic movement factors. In such locations, a digital model would offer little or no advantage.

Selection of Skew Coordinate Axes

There are no rigid controls on the selection of the skew coordinate axes. The only criteria is to minimize the skew of the scan lines by selecting an x axis paralleling the long dimension of the band. When there is a major change in the direction of the band (over 45 deg), it may be desirable to break the band into two or more sections and have a separate skew coordinate system for each in order to keep the skew within reason.

The reference line can be selected with the aid of a small map. Subsequent computation work and the plotting of the skew coordinate axes on subsequent larger scale maps is greatly facilitated if a reference line is selected which will pass through a number of standard state plane coordinate grid intersections. This would correspond to lines with a tangent of the bearing equal to 1, ½, ⅓, ¼, etc.

Once the bearing of the reference line and the state plane coordinates of one point on the line have been selected, it is explicitly fixed in space as an absolute data reference system.

Terrain Data Procurement

The two basic sources of terrain data are the topographic map and the stereomodel. In the case of taking data from an available map, the skew coordinate system (reference line and scan lines) is plotted on the map and data taken off manually or with the aid of automatic measuring and recording devices. In the case of the stereomodel, the skew coordinate system is plotted on the manuscript or the scanning system is oriented and indexed with the aid of numerical readout values. A scanning system and automatic digital readout system for double projection plotters which greatly facilitates the taking of terrain data for the digital terrain model approach has been developed at M. I. T. for the Massachusetts Department of Public Works. The full potential efficiency of the digital terrain model approach is only realized with such an automatic instrumentation system, but it can still be used to advantage when such instrumentation is not available.

One of many possible approaches to the use of the digital terrain model approach with regard to data procurement for a three phase application is as follows:

1. During the reconnaissance phase, if the topographic features governing the location do not clearly indicate the best general route, a band several miles or more in width can be digitized using an existing USGS topographic quadrangle map or a newly prepared reconnaissance scale map as the source of data. The digital terrain model would permit the investigation of a number of possible routes with an earthwork accuracy consistent with the reconnaissance phase.

2. Based on the reconnaissance phase results, a route is selected for more detailed attention in the preliminary location phase. Several alternates are possible in the use of the digital terrain model in the preliminary location phase:

   a. A standard 1 in. = 200 ft, 5 ft contour interval map of a mile wide strip can be obtained. From a study of the map, a ½ mi or narrower band can be selected for digitalization using the map as the data source or for more accuracy by resetting and using the stereomodels used to compile the map.

   b. If the band to be digitized can be selected directly from the reconnaissance study, the digital data can be otained from the stereomodels at the same time they are set for compiling the map. In this case, the mapping limits may exceed or be the same as the digital model limits.

3. The use of the digital terrain model in the final location phase will be primarily to refine the line selected in the preliminary location phase and to provide earthwork quantities for payment purposes. There may or may not be a major amount of shifting of the line in the final location phase, but the digital terrain model removes the problems associated with such shifting in allowing considerable freedom for optimizing the line from the standpoint of earthwork.

The digital data for final location studies would be obtained from the same stereomodels used to compile the large scale planimetric maps which serve as the design base maps. In this case it probably would not be necessary to contour the normal mapping limits but to compile small interval contours only in the vicinity of interchanges, bridge sites, and similar features. In addition to the digital data for obtaining earthwork, it probably would be desirable to obtain profile data for major drain lines and in other special design areas.

The above is only one approach to the data procurement problem. Many others are possible, depending on the extent to which the advantages of the digital terrain model are applicable.

Selection of Trial Lines and Data Processing

The highway engineer is solely responsible for the selection of the trial solutions to the location of the highway. The initial selections will be based primarily on judgment based on a study of the best available map, and a consideration of the many factors which influence the location of a highway.

For each trial horizontal alignment, the highway engineer must furnish the state plane coordinates of the origin, terminus, and each P.I. and the curve radius to be used at each P.I. This data, plus the terrain data previously obtained and already stored on computer input material, serves as the input for the first run through the computer. Based on a stored computer program, the electronic computer prints out the centerline geometrics (stations, P.C.'s, P.T.'s, etc.) and the existing ground elevati elevation of station points along the centerline. It would also be possible to obtain the profile data for any other profiles such as 50 ft to each side of the centerline or an average of the centerline and two or more offsets.

The existing terrain profile data would be automatically plotted by an xy point plotter or line plotter. Without such a plotter, it would be necessary to manually plot the profiles. This would place a practical limit on the number of trial lines it would be feasible to investigate.

With the plotted profiles, the highway engineer would select one or more trial grade lines for each trial horizontal alignment. The data required from the highway engineer for defining the vertical alignment would be the approximate station and elevation of each VPI, the origin, and the terminus, and the length of each vertical curve.

The final input data for which the highway engineer is responsible includes the cross-section design information. The highway engineer specifies the cross-section design criteria for the particular project, (widths and slopes of roadway elements, and side slopes for different conditions of cuts and fills). The basic design templet and design specifications are stored in the computer and the proper templet for each station determined by the computer according to stored instructions. Following the automatic design of the templet at each station, the computer determines the cross-sectional areas and earthwork volumes.

Point Classification

In the M.I.T. computer programs, allowance has been made to classify each terrain point. If the material at each point is classified by soil type (such as rock, peat and sand) the computer will accumulate the earthwork volumes of each type separately. Such classification information might be furnished by air photo interpretation. In the M.I.T. automatic digital output instrumentation system, the point classification is set on a decade dial and the recording performed automatically. The operator changes the setting when he passes from one classification zone to another. Many other such special features to extend the usefulness of the digital terrain model are being investigated.

The Digital Cost Model

The digital cost model approach to highway location evaluation is similar to the digital terrain model concept except that the "z" ordinate has the dimensions of dollars instead of feet. The "z" dimension represents the summation of the other location factors such as right-of-way cost, construction material costs, and other such factors in addition to earthwork which can be reduced to the dimensions of dollars per unit of highway. Traffic benefits would be reflected as a profit instead of a cost. Computer analysis of the digital cost model would have as its mission to determine the most economical solution to the highway location problem. Naturally such a system would have many practical limitations but could serve as a valuable tool and guide for the highway engineer. Its possibilities are more potential than real at the present time.

Research on the digital cost model approach was initiated at M.I.T. during the summer of 1956 and continues as an active subject of investigation. However, it is still in a very early stage of development and considerable work must be done before it reaches operational form even in an experimental sense. It is mentioned in this paper only to report that such research is underway.

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