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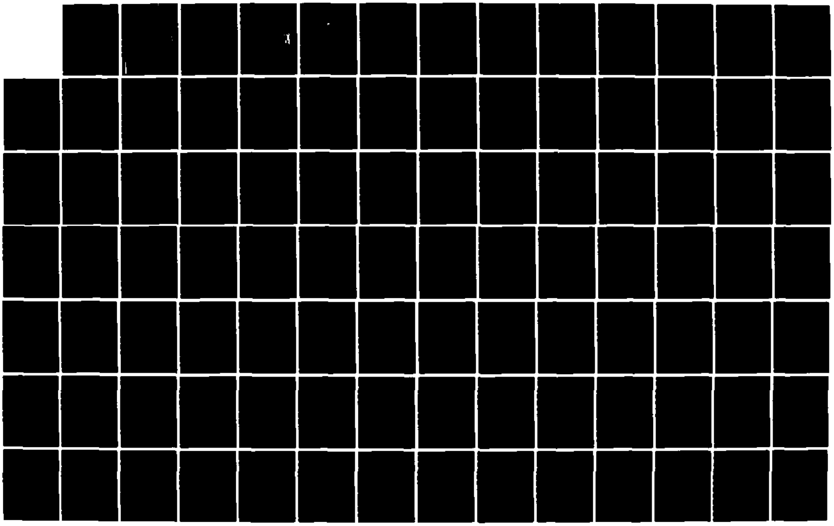

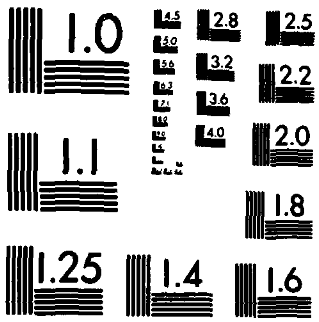

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The Pennsylvania State University

The Graduate School

Department of Civil Engineering

Optimizing Earthwork Estimating for Highway Construction

A Thesis in

Civil Engineering

by

Felix Thomas Uhlik III

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

August 1984

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ABSTRACT

The purpose of this research was to advance the state-of-the-art in earthwork estimating of highway projects. The thesis concentrated on the uncertainties associated with calculating the quantity of rock in cut areas, estimating the fleet production, and selecting the optimum distribution of material between cut and fill areas.

Estimation of the quantity of rock was achieved by using chance-constrained linear programming -- a technique that allows the user to transform stochastic quantity constraints into deterministic ones.

The variability in fleet production was accounted for by using three-value, PERT-type estimates for each of the following components of earthwork: (1) excavation (including loading), (2) hauling, and (3) compaction (including unloading). The user further defines his estimates by selecting a "confidence factor" that represents the probability of not exceeding the target (or middle) value of the three-value estimate.

A standard linear programming (LP) formulation, modified by the chance-constraints, was used to determine the optimum cut/fill distribution as well as the most efficient location for waste and borrow sites.

The proposed system can be summarized in four steps. First, the user inputs cost data for each section (such as 1000-foot intervals) of roadway. Values (three-values for a

probabilistic or a single-value for a deterministic estimate) are entered for excavation, haul, and compaction costs. The second step is the LP formulation including the chance-constrained rock quantities. The third step involves simulating the cost coefficients (determined in step one) resulting from the LP solution in order to produce a cost range. The fourth and final step is a comparison of the cost ranges determined in step three with the cost ranges provided by normal LP sensitivity analysis in step two.

The system was applied to a highway project in Pennsylvania, and the proposed system was compared with other more traditional estimating methods.

The conclusions reflect the fact that, although probabilistic estimating is in its infancy, it has great potential for reducing the risk and increasing the profits of earthwork contractors.

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Finally, the writer wants to thank his wife, Nancy, for all her work involved in the typing, proofing, and re-typing of this thesis. Without her able assistance, support, and love this thesis would continue to be a vision rather than a reality.

CHAPTER ONE

INTRODUCTION

Probabilistic estimating and optimization via linear programming are applied to earthwork estimating in this thesis. Both of these techniques were pioneered many years ago in systems development and operations research applications. Within the construction industry, however, the application of these techniques is in its infancy. The purposes of this chapter are to: (1) orient the reader to the topic of earthwork estimating, (2) state the significance, objectives, scope, and limitations of this study, (3) report the results of preliminary research, and (4) explain the organization of the thesis.

Problem Context

Earthwork operations often play a significant role in highway construction. On many projects, earthwork represents the major item of work and the accuracy of its estimate affects all concerned parties. Earthwork estimating, however, remains an enigma because in spite of its importance there is no concensus about which method produces the most accurate estimate. In fact, almost every contractor, consultant, or design agency will estimate earthwork in a slightly different manner.

The traditional earthwork estimating technique can be categorized as deterministic in that many of the significant parameters are considered to be constant. In reality, of course, production rates and equipment costs vary and unless the "overestimates" compensate the "underestimates" an overall estimating error occurs. A basic problem with a deterministic estimate is that it doesn't provide an indication of the potential total error in the estimate nor does it provide any clues as to which activities tend to provide the greatest potential for estimation errors. Such information would be very useful to contractors and design professionals.

The proposed research will focus on optimizing earthwork estimating for highway construction in Pennsylvania. New estimating techniques incorporating elements of probabilistic estimating and linear programming will be developed and the results obtained will be compared with existing techniques.

Significance

Although estimating represents only one part of the construction process, a valid argument proposes that it is the most important element for both owners and contractors. The owner's concern centers around funding a project and getting it finished within certain time and cost constraints. An accurate estimate is the only way these objectives can be achieved. Contractors, on the other hand, are concerned with success in the competitive bidding process and with making a profit (or at least avoiding a loss). Again, an accurate estimate is the only way these objectives can be met. Existing estimating techniques that are used, even though they have evolved through the years, seem to offer only "hit or miss" reassurance with respect to accuracy. Many contractors do not even bother to plot a haul-mass diagram, let alone try to mathematically optimize the cut/fill distribution through linear programming techniques. Deterministic estimating -- the selection of a single value without regard for its variability -- has become ingrained within the construction industry. While the concept of a three-value probabilistic estimate (i.e., PERT-type with low, mean and high values) is not new, very little application of this technique has appeared in the construction industry.

This research seeks to remedy these shortcomings in the earthwork estimating area of the construction industry. The proposed technique consists of combining three-value probabilistic models with linear programming. The technique is applied to a highway construction project within Pennsylvania as a case study and the results are compared to the traditional estimate prepared by both Pennsylvania Department of Transportation (PennDOT) and the contractor that was awarded the project. Analysis of the findings of this case study considers the tradeoff of additional information (i.e., optimum cut/fill distribution, parameter sensitivity, etc.) obtained from the research and the time required to prepare the estimate as compared to the traditional earthwork estimating process.

Objectives

The research undertaken was intended to remove some of the limitations present in a deterministic estimate. The writer's intent was to analyze existing practice in earthwork estimating and then to interpret and implement the changes that are required in order to advance the state-of-the-art. In particular, the following objectives are designed to improve earthwork estimating by quantifying the inherent uncertainty.

1. Develop a methodology that incorporates uncertainty into the calculation of the quantity of rock for use in unclassified excavation estimates.
2. Develop a methodology that incorporates probability into the cost elements for use in earthwork estimates.
3. Develop a linear programming (LP) model that can be used to determine the optimum cut/fill distribution of earthwork quantities.
4. Develop a cost estimating system, utilizing the above techniques, that provides as an output a cumulative probability curve for the total unit cost.

Scope and Limitations

This research only focuses on earthwork estimating for highway construction. The boundaries of the study can be defined as those actions which must occur between the time when a set of plans and specifications is available and the time when an estimator completes estimating the direct costs of the earthwork. While the proposed research is directed to a contractor's estimating methods, it is also applicable to engineering estimating.

The research was directed at unclassified excavation where determination of the quantity of rock is a critical task for the contractor. The thesis does not include tunneling or pipeline (trenching) operations.

The research addresses the direct costs for a unit-price earthwork project. Job and project overhead, markup, inflation, interest, contingency, bond costs, profit and subcontractor costs are not considered. The following aspects of construction also are not directly included in this research: bidding strategy, equipment economics, costs control, and cash flow analysis.

Preliminary Research

The preparation of an earthwork estimate requires the consideration of numerous factors, with the following three areas being the most important: (1) earth/rock composition, (2) cut/fill distribution, and (3) fleet production. The first area is significant because PennDOT requires contractors to submit bids on unclassified (Class 1) excavation by determining a single unit price for all material, whether it is soft earth or solid rock. The unit price for Class 1 Excavation also includes haul, placement, compaction, rehandling of material, and disposal of unsuitable materials. On some projects, a separate price is bid for borrow material. While the total cut quantity is known, the respective quantities of earth and rock are not supplied (nor are they known) to bidders who must then estimate or predict the composition of the material in the cut areas. Naturally, rock excavation is significantly more costly than earth removal and a high estimate of the percentage of rock can easily cause a contractor to lose a prospective project or, even worse, go bankrupt on a project in which his estimate of rock presence was too low.

The cut/fill distribution on a large earthwork job is critical because the hauling costs must be minimized in order to afford the contractor maximum profit. While excavation (assuming earth/rock quantities are known) and embankment (placement and compaction) costs are relatively fixed, the haul costs vary with the distance that the material must be transported. While the disposition of the cut material may be obvious in some cases (as in an adjacent fill area), typical projects require decisions to the questions of the quantities and locations where the cut material should be routed. Typically, earthwork cuts and fills do not balance so that further decisions must be made regarding borrow (for additional fill) and waste (for excess cut) routing.

Fleet production is the final general area of interest. Earthmoving is an "equipment intensive" operation and a fleet usually refers to a specified group of equipment performing a certain earthmoving activity. The proposed research will consider fleet production through the concept of cost elements. Contractors normally estimate earthmoving costs by summing cost elements which are obtained by dividing the fleet costs per unit of time by the fleet production in cubic yards (cy) per unit of time (resulting in cost per cy). For example, if fleet costs and production are on a daily basis, the total unit cost would be calculated as follows:

$$\text{Total cost} = \frac{\text{fleet cost (\$/day)}}{\text{fleet production (cy/day)}} = \text{\$/cy} \qquad (1)$$

While fleet costs are subject to some fluctuation, historical records of past fleet costs show this item to be relatively predictable for estimating purposes. Cost elements (cost per cy for excavation, hauling, and embankment), however, are subject to considerable variation due to parameters, such as weather, haul road condition, type of material, and operator performance. Of course, fleet production is the most significant parameter affecting cost elements. Any number of unpredictable site-specific factors, such as weather, labor strikes, and accidents, can drastically affect fleet production. Contractors must try to control production so that actual output approaches the value used in estimating the project. If it does not, the projected profit changes accordingly.

The general topics discussed above provide the focus for the proposed research. Existing techniques for addressing these three areas of concern will be reviewed and new techniques will be developed during the course of the proposed research effort.

Organization of Thesis

The thesis is organized so that the reader can first obtain an understanding of the background and framework in which the earthwork estimating problem resides. Consequently, Chapters Two and Three summarize the pertinent literature and current practice, respectively, relative to earthwork estimating. Chapter Four discusses the important topic of uncertainty and explains the proposed probabilistic models formulated to incorporate uncertainty within an optimized system. Chapter Five presents the LP method of optimizing the cut/fill distribution of earthwork. Chapter Six provides the details of the proposed system and Chapter Seven relates this system to an actual highway project as a case study. Finally, Chapter Eight presents the conclusions of this research effort and discusses pertinent areas requiring further research.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, a summary of pertinent literature is presented. The organization proceeds from the very general (textbooks) to the specific (theses) with comments that address the significance and applicability of each work to this thesis.

Textbooks

There are relatively few texts that treat earthwork in detail. Moving the Earth, by Nichols (1962), is one of the epic works on excavation. It includes information on every aspect of earthmoving -- from clearing to compaction. The text is written for professionals in the construction business and, therefore, is heavily weighted toward practical applications with very little background theory included. The primary purpose of the book is to provide a comprehensive description of construction methods and machinery. Nichols does present the technique of developing haul-mass diagrams but stops far short of addressing the optimization of cut/fill distribution.

Excavation Handbook by Church (1981), is a more current text that addresses earthwork estimating. This book is geared more towards the design professional and is consequently more rigorous in its presentation. The text is an excellent source of information for engineering geology and includes an entire chapter on the calculation of quantities for excavation. It provides complete coverage of the mass diagram technique and even includes charts that can be used to expedite the calculation of quantities. While the text devotes an entire chapter to earthwork estimating, it discusses bid preparation only from a deterministic point of view. The variability and uncertainty aspects of earthwork estimating are not addressed.

A recent book, Construction Cost Estimating for Project Control, by Neil (1982), briefly discusses the role probability and variability play in construction estimates. While he does not discuss earthwork estimating directly, the suggested techniques and theory would apply. Neil describes a probabilistic approach to estimating that allows the user to associate a quantified risk with a bid price. It appears that the technique suggested by Neil could be applied to earthwork estimating in the areas of rock quantity and fleet production estimating.

Mathematical Foundation for Design: Civil Engineering Systems, by Stark and Nicholls (1972), is an excellent text that relates mathematical modeling to practical civil engineering problems. When discussing linear programming techniques, the authors show how such a technique can be applied to a cut/fill situation. While the use of linear programming to solve allocation problems is not new, the authors' suggested use for earthwork estimating warrants additional study to determine the feasibility of further refinements and applications. This writer believes that linear programming possesses untapped potential as an estimating tool.

Estimating Manuals

Estimating manuals, guides, and equipment manufacturer performance handbooks comprise the available information normally used by design professionals to develop an earthwork estimate. The principal estimating manuals used are those published by Means, Dodge, and Richardson. They all provide unit costs for earthwork estimating based on the equipment (fleet) selected. For scraper operations, they base unit costs on haul distance (and consequently, fleet size) while for other equipment, the unit costs vary according to the capacity (size) of the equipment. The techniques contained in these manuals are deterministic and offer no assistance in determining the average haul distance on a particular job. The RICHARDSON SYSTEM is the only one that provides information and charts for calculating quantities of earthwork.

Aside from the estimating manuals discussed, equipment manufacturers are the only other public source of information for estimating earthwork. Caterpillar, International, Euclid, and Terex are the leading manufacturers of heavy earthmoving equipment and each of them publish "performance handbooks/guides" which, ostensibly, are designed for earthwork estimating. This writer's discussion with approximately a dozen earthmoving contractors within Pennsylvania, however, indicates that this source of estimating information is seldom, if ever, used by contractors. Most contractors view manufacturer's performance data as a "selling motivator" and feel that the use of manufacturer's data inevitably results in overly optimistic cost estimates that would produce losses instead of profits if used for bidding purposes. The manufacturer's handbooks do serve, however, to illustrate a detailed technique for deterministically estimating earthwork. While they indicate how to compute the elements comprising a cycle of an earthmoving operation, they do not provide any information or rules regarding fleet composition, quantity take-off, or cut/fill distribution.

Journals

Several articles in the Journal of the Construction Division have addressed elements of earthwork estimating. Spooner (1974) and Vergara and Boyer (1974) approach the topic of probabilistic estimating on a general level. In his article, Spooner illustrates how it is possible to arrive at a mean and variance of the total estimate based on the means and variances of the individual elements. He uses subjective three-value estimates to define the probability distributions of each of the elements. He contends that by imposing a range on an estimate, the estimator is relieved of the "tension" involved in picking a single "good" value.

Such a technique appears to warrant application in the earthwork field. Vergara and Boyer describe an application of the principle of successive estimating put forth by Lichtenberg (1971). The idea is to increase the level of detail on those elements having the greatest variance. They use Friedman's (1956) model as a starting point and proceed to develop a relationship between the markup and risk as a function of the detail of the estimate. The authors suggest the use of a three-value estimate, similar to the above mentioned, as an approximation to obtain the probability distribution for a subjective estimate.

Mayer and Stark (1981) and Nandgaonkar (1981) studied the problem of earthwork logistics or transportation and illustrated the use of a linear programming formulation. Nandgaonkar formulated the cut/fill distribution as a classical transportation problem and used an earthwork project in India as a case study. It was not evident how Nandgaonkar accounted for swell or shrinkage from cut to fill areas and the possibility of borrow/waste sites were not discussed. Mayer and Stark expanded the original formulation suggested by Stark and Nicholls (1972) and incorporated swell/shrinkage factors and the use of borrow and waste areas. Their deterministic approach did not explicitly formulate a model that handled different types of material (i.e., earth and rock) but alluded to the possibility.

Theses

A final area of background information and sources is thesis research in the earthwork area. Clemmens (1976) analyzed scraper operations using simulation. After collecting data he used regression analysis to approximate the relationship between haul distance and cycle time. Burton (1977) also did research on cycle time prediction. He compared traditional deterministic estimating with a modified system used by a particular contractor. Both Clemmens and Burton focused on only one small aspect of the earthwork estimating process. Neither of the studies dealt with the variance of the total earthwork estimate.

Love (1982) developed an interactive APL-based computer program that incorporated a significant portion of the estimating techniques found in equipment manufacturer's handbooks. While Love's system certainly speeds-up the laborious chore of detailed estimating according to equipment specifications, it only deals with the deterministic approach. Current work is underway to expand Love's system to incorporate profile analysis, haul-mass diagrams, and compaction. The value of such a system is that it can produce a relatively rapid deterministic estimate.

Neil (1978) addressed cost estimating concepts on a much broader basis than that of the above noted theses. He examined the reasons for poor estimates, reviewed methods to minimize estimating error, and conceptually developed an overall system for estimating a complex project. Neil's system integrates the estimating, scheduling, and cost control functions through a code of accounts that he developed to support his proposed system.

The major value of Neil's thesis to this writer is that it provides a rather comprehensive coverage of existing systems designed to handle risk analysis in construction estimating through the use of basic probability concepts. One such system, described by Van Tetterode (1971), is incorporated into the estimating system developed in this thesis.

Schremp (1978) studied construction estimating from a philosophical perspective. He examined the human behavioral characteristics of estimating as well as the traditional treatment of probability and statistics. Although topics ranging from expectation to bidding strategies are addressed, the coverage is in a narrative form without the appearance of equations.

A major contribution of Schremp's study was the evaluation of the estimation process from the humanistic or behavioral point of view. In particular, Schremp discusses the complex issue of uncertainty from both a technical and philosophical viewpoint and emphasizes the importance and implications of both the statistical and subjective elements of estimating.

Summary

The foregoing summary of relevant information demonstrates that there are, in fact, gaps in the current field of knowledge about earthwork estimating. While several peripheral areas have received attention, there is no evidence of a comprehensive study of earthwork estimating, particularly one that incorporates probabilistic models.

The next chapter discusses current earthwork estimating techniques. It includes sections on estimating guides, a computerized approach, contractor methods, and the system used by PennDOT.

CHAPTER THREE

CURRENT EARTHWORK ESTIMATING TECHNIQUES

Background

Earthwork operations consist of activities, such as ripping, excavating, loading, hauling, drilling and blasting, and compaction. The estimating process for a contractor begins with receipt of a set of plans and specifications and ends with the submittal of a bid. The actions taken between these two activities usually determine the success or failure of a contracting firm with regard to obtaining a project.

The first step in estimating is to review the plans and specifications. Assuming a contractor decides to bid on the project, he must next determine the level of detail required. A tradeoff exists between the cost of preparing an estimate in detail and the higher risk of submitting a bid on a project with a less detailed estimate. Next, the estimating units must be determined. Since most earthwork projects are bid as unit-price contracts, typical units are loose cubic yard (LCY), bank cubic yard (BCY), and compacted cubic yard (CCY). The estimator's next step consists of a "quantity takeoff" in which he determines the amount of material to be excavated, ripped, trenched, loaded, hauled, and compacted. Finally, the estimator is ready to apply production rates (i.e., BCY/Hr. for example) and compute unit costs. This step contains the most uncertainty and accounts for the major limitation in the deterministic estimate. The reason, simply, is that production rates depend on several parameters and it is an approximation to consider them to be constant.

A more realistic approach to earthwork estimating entails consideration of quantities, particularly the earth/rock composition, and the related costs as random variables. An estimate that accounts for such stochastic variables, while it may be more difficult to compile, will produce an estimate that more realistically approximates the actual cost than a strictly deterministic estimate. Chapter Four treats the subjects of uncertainty and probabilistic estimating, respectively, as they apply to earthwork estimating.

Estimating Guides

As noted earlier, there are at least three major estimating guides used within the construction industry: (1) Dodge Guide, (2) RICHARDSON SYSTEM, and (3) Means. Of these the third, Means, is geared primarily towards building and light construction and will not be considered further for highway construction.

Dodge Guide to Public Works and Heavy Construction (1982) is representative of the information available to the estimator. It is noted:

> The labor and equipment costs are calculated using the listed production rates, wage rates, and equipment operating cost, and are based on observation of many contractors to

> determine current practices. This method provides data that represents the actual cost of operations, rather than a theoretical cost of the methods that could be used. (p. II)

The assumed contractor efficiency is eighty percent and the fleet size is based on that required to maintain the editor's estimated production rates. The Dodge Guide lists construction cost data in three sections: (1) construction, (2) design, and (3) planning. As listed, the degree of detail decreases between sections 1 to 3, with the intended use corresponding to the section name. The first section would be used for preparing a bid since it is the most detailed. It is arranged according to length of haul (for scrapers and trucks), type of material and size of equipment (for excavators), and rate of delivery (for placement and compaction). The user of this guide must decide on haul length, type of material, and equipment allocation (both type and number of equipment items).

The RICHARDSON SYSTEM provides information similar to that in the Dodge Guide as well as additional estimating information. For example, two methods of calculating earthwork quantities are presented along with time-saving tables. Specific equipment specifications (for Caterpillar) are included as well as selection charts for equipment fleets (i.e., number and type of each equipment item) for scraper operations. As with the Dodge Guide, the estimator must enter the tables with the type of material and length of haul for scraper operations. Unlike the Dodge Guide, however, the RICHARDSON SYSTEM provides production dozing estimating data but does not consider the other methods of site grading, such as front-end loader and shovel operations. Also, the RICHARDSON SYSTEM provides both direct and indirect costs for earthmoving operations while the Dodge Guide requires the user to supply his own indirect cost markups.

It is not known if either of the above guides has a better "track record" for earthwork estimating or if, in fact, such a judgement could be substantiated. The purpose of their inclusion in this thesis is to recognize their existence and use and to provide for completeness in the coverage of earthwork estimating.

SEMCAP Summary

Love (1982) developed a Systematic Earthmoving Cost Analysis Program (SEMCAP) that computerized the estimation of certain earthwork operations. Initially, SEMCAP included ripping, drilling and blasting, loading by both power shovel and front end loader, truck hauling and scraper operations. Nelson (1983) expanded SEMCAP by incorporating profile analysis and compaction capabilities. Further work by Marshall (1984) provides for plotting haul-mass diagrams and refines SEMCAP by making it easier to use.

SEMCAP is an interactive estimating system programmed in the APL language, but knowledge of APL is not necessary to use the system. SEMCAP uses the estimating techniques of the Caterpillar Performance Handbook (1979) as a basis but also provides performance data from Euclid, International, and Terex equipment manufacturers. The user can select parameters from the various manufacturers since SEMCAP displays such tabular data at appropriate points in the estimating process.

SEMCAP is a strictly deterministic system but offers several advantageous features. It is certainly less time consuming than manually preparing a similar estimate, but, more importantly, it allows the user to easily manipulate input data and observe production and cost variations. As such, it is useful for sensitivity analysis. SEMCAP is a very flexible system which allows the user to analyze a wide range of problems and operational configurations by selective usage of the available functions. These are presented in menu format.

The features of SEMCAP make it a valuable teaching and learning tool for educators and students. While it can be used for estimating by engineers and contractors, this writer's contact with earthwork contractors and design professionals indicates very little demand for or usage of SEMCAP. The major reasons for this perceived reluctance to use SEMCAP is simply that: (1) earthwork contractors do not believe in the validity of equipment manufacturer's estimating techniques, and (2) earthwork contractors, in general, do not maintain the type of historical data needed for input in SEMCAP (i.e., cycle time components, material densities, travel speeds, etc.). Contractors generally maintain only historical production data for their various equipment fleets (in some cases for individual equipment items). Such data are average production figures (i.e., cubic yards per day) that incorporate the specific constant and variable parameters that comprise fleet production. The historical production data is relied upon by contractors because it represents actual production that has been achieved. The inherent uncertainty is evident by observation of the scatter or range of the values. It is not difficult to understand why contractors are reluctant to use a deterministic system, such as SEMCAP, which provides no information regarding the variability of the estimate obtained. Consequently, contractors usually rely on their own estimating method and develop a range for their estimate rather than relying on one value. The next section will discuss some typical estimating techniques used by earthwork contractors in Pennsylvania.

Contractor Estimating Methods

Part of the preliminary research undertaken included interviewing a sample of earthwork contractors within Pennsylvania. With about two dozen such contractors available, six were eventually interviewed and they provided the information that is summarized in this section. For those unaccustomed to obtaining research data from contractors, particularly if it relates to estimating and/or bidding, the difficulties involved cannot be appreciated. Most contractors, and even design agencies, consider their estimating techniques to be confidential. Highway contractors, who normally engage in competitive bidding to obtain their work, are highly sensitive to divulging any information that could possibly reach a competitor and provide a bidding advantage. When this confidentiality is combined with a hectic work schedule during the construction season, it is not difficult to understand the magnitude of the problem associated with data gathering.

Earthwork Contractors

Table 3-1 provides a summary of some key characteristics of the six contractors who were interviewed. In keeping with their wishes, the company names are withheld and they are referred to as contractors one through six. Column one is the average annual business volume, the percentage representing construction work being shown in parenthesis. The remaining percentage of annual volume for contractors one, two, and six is attributable to material supplies since these contractors own several quarries and asphalt plants. All contractors, except number three (which is more diversified), are primarily highway contractors and relatively small in size when compared to the top multi-billion dollar construction firms. The second column indicates that most of them choose to limit the geographic location of their projects to Pennsylvania. Column three indicates that the contractors own essentially all of their

TABLE 3-1

Comparison of Representative Pennsylvania Earthwork Contractors

Contractor	(1) 1982 Annual Volume of Construction ($ Million)	(2) Geographic Coverage	(3) Equipment Owned vs. Leased (%)	(4) Level of Historical Record Keeping D-Detailed L-Limited N-Not Used
1	35	State of Pennsylvania	99	D
2	18	Central Pennsylvania	100	L
3	400	International	99	D
4	8	Within 100 miles	80	N
5	2	Within 100 miles	100	L
6	9	Within 25 miles of an owned quarry	99	L

earthmoving equipment. The fourth column represents a subjective evaluation of their historical record-keeping based on interviews with their personnel. Naturally, the cost accounting system along with the available computer support has a direct bearing on the extent of the recorded historical data. A "detailed" rating was given if the company maintains production as well as cost data for individual pieces of equipment and for fleets. A limited rating implies the recording of only cost data for individual equipment items and production data on a fleet basis. The "not used" category was given to contractor four in view of the fact that the cost accounting system had only recently been converted to a computerized operation and, therefore, very little data had been stored.

At the end of the last section, contractor confidence in their own historical data was cited as a reason why contractors don't use an equipment manufacturer's approach to estimating. At this point, it should also be noted that the experience of the estimator also contributes to the adoption of unique estimating techniques by contractors. Perhaps this is no more evident than for the calculation of earth/rock quantities within cut areas. Experienced estimators visit and walk along the entire project site. They look for tell tale signs of subsurface water, such as swampy fernlike vegetation, because they know that both diverting the water table and wet blasting holes increase project cost. The successful estimator usually drills test holes in the major cut areas since he knows that his estimate of the percentage of rock could well mean the difference between his firm getting the job or not. During the test drilling, the estimator may time the bit penetration rate with a stop watch so that he can relate the anticipated production to historical production rates and possiblv gain additional information about the soil/rock classification. Obviously, a contractor who has completed or who is engaged in earthwork operations located in the same geographic location as a new project has distinct advantages over his competitors. The above factors provide only a hint of the importance of experience but they also illustrate a few of the many uncertainties associated with earthwork estimating.

Steps in Estimating Methods

Almost every contractor interviewed used a different estimating method although certain steps were fairly consistent among all six. The following steps, perhaps in slightly different order, are used by the majority of the six contractors:

1. Field drilling
2. Plotting rock lines -- Calculation of volumes
3. Determining cut/fill distribution
4. Determining fleet composition/costs
5. Applying production rates.

<u>Field Drilling</u>. Field drilling is done by contractors during the bid preparation stage before the contract is awarded. It serves three primary purposes: (1) data is obtained about the depth and type of rock in cut areas, (2) data is obtained about drilling production rates, and (3) familiarity with the project site is achieved. The first purpose is of paramount importance because it provides exclusive (not available to competitors) information that aids in reducing the uncertainty related to earth/rock composition. While competitor contractors are also free to drill test holes, they are responsible for selecting locations, number of holes, and interpretation of data.

<u>Plotting Rock Lines -- Calculation of Volumes</u>. The next step, plotting of rock lines, involves using the data obtained from field drilling, as well as any information supplied with the plans (i.e., boring logs, soil profiles, etc.), to approximate the location of rock layers. The purpose of this procedure is to quantify the amount of rock in cut areas. Drill holes are marked on the profile drawings with an indication of location as "xx feet" left or right of centerline or on centerline.

Next, the corresponding cross-section drawings are obtained and the field drilling data is plotted on them. Ideally, enough data points are available to establish the rock lines at a regular interval on the cross-sections. Once the rock lines are established, the cross-sectional areas are computed. This is done either manually or electronically with a digitizer. Once the areas are determined, the volumes can be computed. The most common method of volume computation is the average end area method which uses the following equation:

$$V_i = D\left(\frac{A_{1i}}{2} + \ldots + A_{(n-1)i} + \frac{A_{ni}}{2}\right) \div 27 \qquad (2)$$

where V = Volume in BCY

D = Distance between cross sections in ft

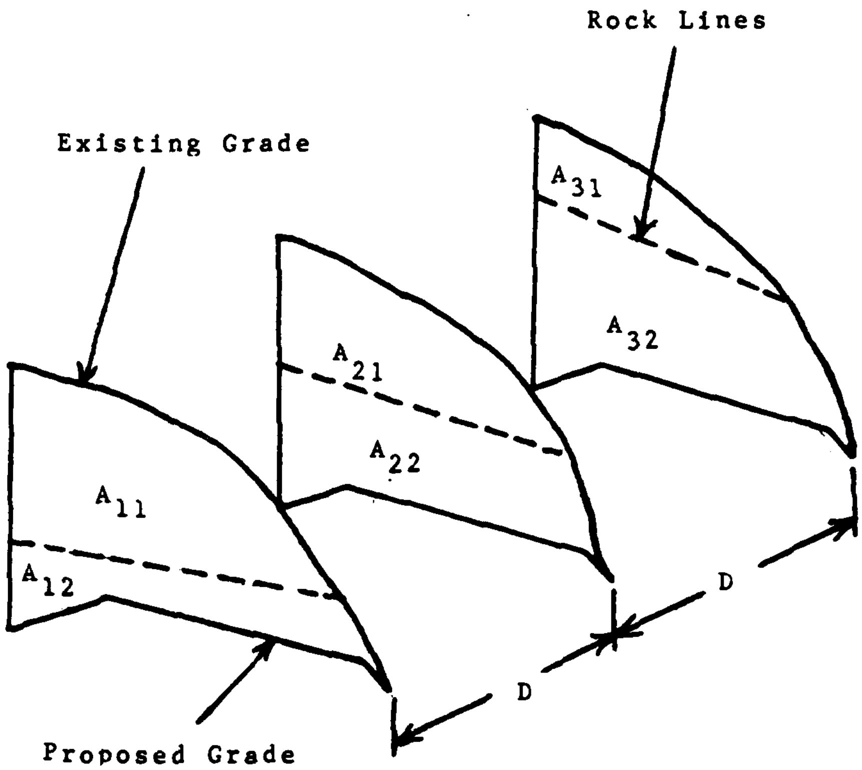
i = Type of material (1=earth, 2=rock)

$A_{1i},\ldots,A_{ni}$ = Areas of cross sections in ft^2 (n is the number of sections)

27 = Conversion factor for ft^3 to BCY

Figure 3-1 illustrates the application of the end area method for a section consisting of three cross sectional areas (i.e., n = 3). The average end area method is not exact and tends to slightly overestimate the actual volume. The precision, however, according to Church (1981) is on the order of $\pm 1\%$, which is normally considered adequate for earthwork estimating. Other more accurate techniques, such as the prismoidal formula, are available for volume computation if the added expense of their usage is warranted.

Determining Cut/Fill Distribution. This is the third general step in the estimating method. Figure 3-2 illustrates a typical profile and haul-mass diagram for a highway project. Although the haul-mass diagram is the commonly accepted technique for accomplishing this step,



<u>Soil Volume, V_1</u>

$$V_1 = \left(\frac{A_{11}+A_{21}}{2}\right)(D)+\left(\frac{A_{21}+A_{31}}{2}\right)(D)$$

$$= \left(\frac{A_{11}+A_{21}}{2}\right)(D)+\left(\frac{A_{21}+A_{31}}{2}\right)(D)$$

$$= \left(\frac{A_{11}}{2}+A_{21}+\frac{A_{31}}{2}\right)(D)$$

<u>Rock Volume, V_2</u>

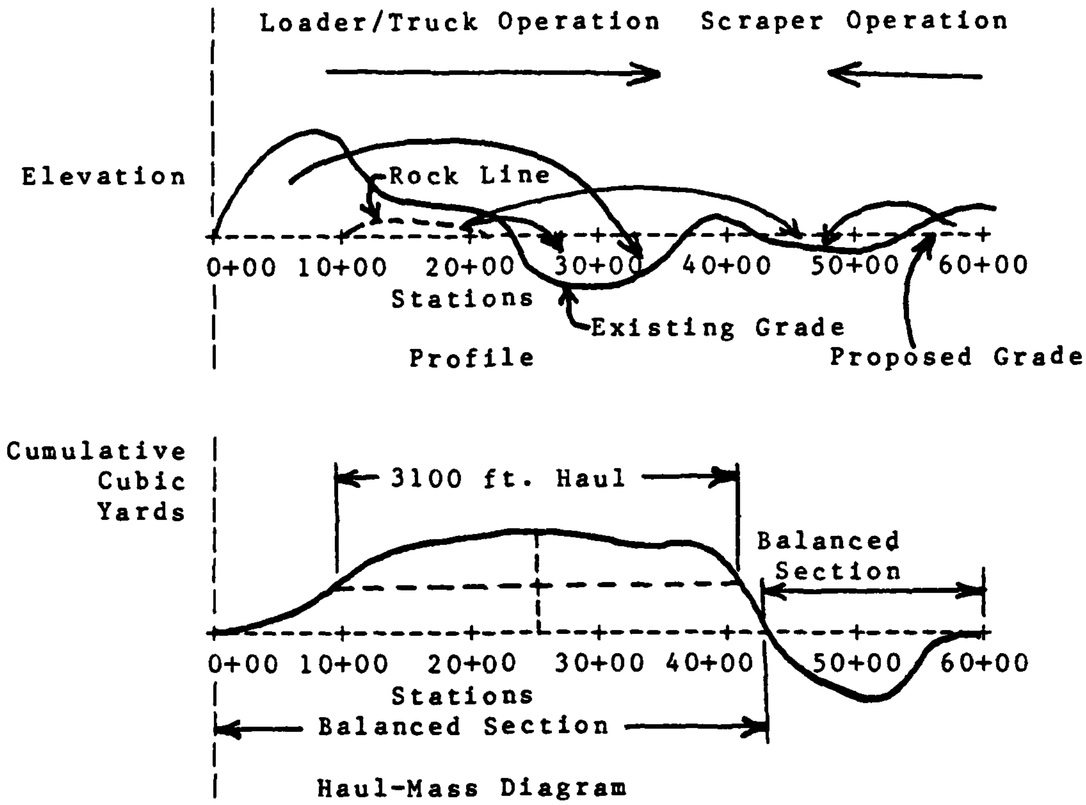
$$V_2 = \left(\frac{A_{12}+A_{22}}{2}\right)(D)+\left(\frac{A_{22}+A_{32}}{2}\right)(D)$$

$$= \left(\frac{A_{12}+A_{22}}{2}\right)(D)+\left(\frac{A_{22}+A_{32}}{2}\right)(D)$$

$$= \left(\frac{A_{12}}{2}+A_{22}+\frac{A_{32}}{2}\right)(D)$$

Total Excavation Volume $= V_1 + V_2$

FIGURE 3-1 End Area Method for Measuring Earthwork (Neil, 1982:215)



NOTES:

1. The arrows on the profile indicate the proposed movement of material.
2. A loader/truck operation was selected for the longer haul while scrapers were used for the shorter haul.
3. The average haul distances are graphically constructed from the haul-mass diagram as follows:
   A. Vertical lines are drawn from the maximum ordinate points to the abcissa.
   B. Horizontal lines are drawn to bisect the lines drawn in step A and extend to the haul-mass curve.
   C. The distances between the intersection points of the lines drawn in step B and the haul-mass curve are scaled along the abcissa and represent the average haul distances from cut to fill sections.
4. The haul-mass diagram above is perfectly balanced (i.e., no excess waste or borrow material is required).

FIGURE 3-2 Typical Profile and Haul-Mass Diagram none of the six contractors interviewed use the haul-mass diagram. Instead, an "arrow allocation diagram" is developed to determine cut/fill distribution. An illustration of an arrow allocation diagram, using the same example as for the haul-mass diagram in Figure 3-2, is shown in Table 3-2. The arrows represent the movement of material from the cut (tail of arrow) to the fill (head of arrow). The arrows are drawn based on the simple principle that cut is distributed to nearest available fill. Experience is required, however, to complete an arrow allocation diagram in a practical manner. Decisions must be made as to the maximum haul length and locations for waste areas if there is an excess of cut. For example, it could be more costly to haul material a long distance to a fill rather than to "waste" the material nearby and procure borrow (additional fill material) at a closer location to the fill. Figure 3-3 depicts such a situation. The arrow allocation diagram, in addition to showing cut/fill distribution, can also be used to compute the average haul distance as shown in the continuation of Table 3-2. The average haul distance is an important parameter because it dictates the fleet composition needed to accomplish the cut/fill distribution determined by the arrow allocation diagram.

Determining Fleet Composition/Costs. The fourth step of the contractor estimating method consists of determining fleet composition and cost. Since this is strictly an individual matter among contractors, it is not possible to

TABLE 3-2

Typical Arrow Allocation
Diagram

Stations (100 ft.)	Excavation (cut in ccy)		Embankment (fill in ccy)	Remarks
0+00 - 10+00	31,400	5,000	5,000	500ft. haul
		400		1500ft. haul
		20,000		2500ft. haul
		6,000		3500ft. haul (No rock in this section)
10+00 - 20+00	340,000	161,600	400	45,000 BCY rock
		178,400		
20+00 - 30+00	43,000	43,000	63,000	9,500 BCY rock
30+00 - 40+00	27,000	27,000	194,600	
40+00 - 50+00	3,000	3,000	420,000	
50+00 - 60+00	283,600	238,600		
		45,000	45,000	15,000 BCY rock
Totals	728,000		728,000	69,500

TABLE 3-2 (Continued)

Typical Arrow Allocation Diagram

NOTES:

1. The volumes listed in the excavation column were converted from BCY to CCY using swell/shrinkage factors. (See Table 5-1 for additional details).

2. The example, shown in the table above, is perfectly balanced (i.e., Total Excavation = Total Embankment). If it were not, arrows would be included to show quantities from borrow areas and/or quantities to waste areas.

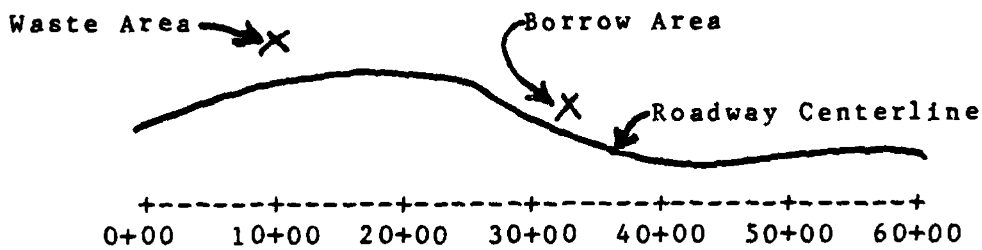
$$\text{Average Haul Distance} = \frac{(\text{ccy} \times \text{Distance})}{\text{ccy}}$$

$$\begin{aligned}(\text{ccy} \times \text{Distance}) &= (5000 + 43000 + 27000 + 3000 + 45000) \times 500 \\ &\quad + (400 + 238600) \times 1500 \\ &\quad + (20000 + 161600) \times 2500 \\ &\quad + (6000 + 178400) \times 3500 \\ &= 1{,}519{,}400{,}000\end{aligned}$$

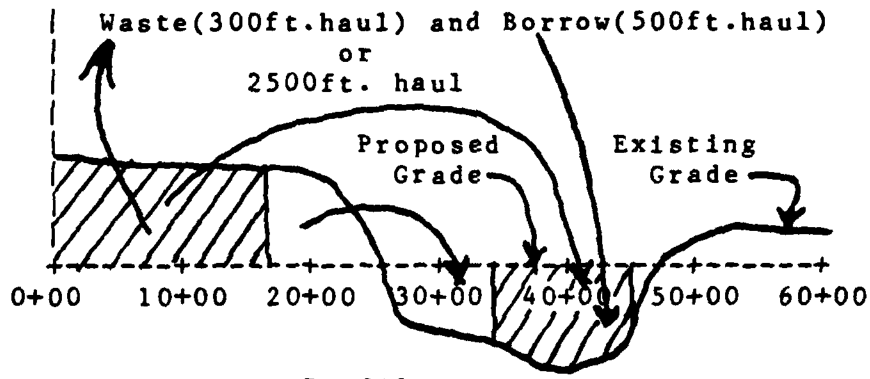
$$\text{ccy} = 728{,}000$$

$$\text{Average Haul Distance} = \frac{1{,}519{,}400{,}000}{728{,}000}$$

$$= \underline{2087 \text{ ft.}}$$



Plan



Profile

FIGURE 3-3 Illustration of the Use of
Waste and Borrow Areas

elaborate on specifics. Obviously, each contractor's fleet costs will be different and the fleet compositions will also vary depending upon: (1) available equipment, (2) average estimated haul length, (3) type of material, and (4) time available to complete earthwork. Note that fleet compositions can, and often do, vary in both the types of equipment (i.e., scraper or loader/truck) and in the number of machines for a project. Figure 3-2 illustrates the use of loader/truck fleets for the longer haul and scraper fleets for the shorter haul. Depending on the four factors mentioned above, the composition of each of these fleets could be varied over the course of the project to meet the contractor's needs. Successful contractors rely on experience to determine proper fleet compositions and on historical data to determine accurate fleet costs.

Applying Production Rates. The fifth and final step consists of applying production rates to the fleet costs computed in step four. For each fleet (i.e., scraper, loader/truck, drilling and blasting, etc.) the fleet cost (in $/day) is divided by the estimated fleet production (in cy/day. for example) and the fleet unit cost ($/cy) is obtained. Fleet production rates are estimated by contractors based on historical data from previous jobs. Usually, the estimator selects two or three average production rates to compute fleet unit cost. In effect, a range for fleet unit cost is created. Table 3-3 provides an example illustrating this procedure.

TABLE 3-3

Example Problem Illustrating the Calculation of Fleet Unit Cost for a Scraper Operation

Scraper Fleet No.	Equipment	Daily Direct Labor Cost ($)	Daily Equipment Cost ($)	Daily Fuel Cost ($)
5	641 Scrapers	908	2700	585
1	D9L Dozer	196	675	180
2	D9 Dozer	182	775	240
1	D8L Dozer	182	450	90
1	CC1 Compactor	179	225	80
1	G-16 Grader	182	180	72
1/2	Water Tanker	73	50	14
1	Pickup	165	12	8
	TOTAL	2067	5067	1269

Total Daily Fleet Cost = $2067 + $5067 + $1269 = $8403

Fleet Unit Cost($/BCY) = Total Daily Fleet Cost - Daily Fleet Production

Possible Daily Fleet Production (BCY/day)	Fleet Unit Cost ($/BCY)
5000	$8403/day-5000BCY/day=1.68
5500	$8403/day-5500BCY/day=1.53
6000	$8403/day-6000BCY/day=1.40

Once a range is established, the estimator can select his estimate of the most likely production value within this range. This step is of critical importance and yet involves enormous uncertainty. The estimator must rely on his subjective judgement to select a production value. Factors that are considered include, but are not limited to; location of project, size of project, logistics (haul road, borrow and waste areas), type of material, weather, recent similar projects, available equipment, quotations from subcontractors, and quality of the labor force. With this number of factors involved (some of which are difficult to quantify), it can easily be recognized that the fleet unit cost contains considerable variability. The next step is to multiply the quantities by their respective fleet unit costs to obtain a total cost. For example, assume the costs for the loader/truck and scraper fleets are as follows (Table 3-3 illustrates the calculation of the scraper fleet cost):

Fleet	Fleet Unit Cost ($/BCY)	Quantity (BCY)
Loader/Truck	1.40	443,000
Scraper	1.68	285,000

The total fleet costs would, therefore, be calculated as follows:

Fleet	Total Fleet Costs
Loader/Truck	$1.40/BCY x 443,000BCY = $620,200
Scraper	$1.68/BCY x 285,000BCY = $478,800

To the above Total Fleet Costs, the contractor would add the blasting cost (using a similar fleet analysis) and a percentage for preparation, clean-up, and any borrow/waste quantities. This total is then divided by the total project quantity (usually in BCY) to obtain a project unit cost ($/BCY) for earthwork.

At this point, the estimator has completed his initial earthwork estimate but may not be finished estimating the job. Most contracting firms review the project estimates in conference style with the company executives prior to submitting a bid. Here management-level factors, such as cash flow position, forecasted workload, inflation, competition, unbalancing of bids, and markup, for the entire project are considered. Depending on the outcome of this conference, the estimator may have to re-estimate the earthwork portion of the project. The range of fleet production values comes into play at this point. Depending upon whether the management concensus was to increase or decrease earthwork costs, the estimator can readily choose an appropriate revised fleet cost and re-compute the estimate with relatively little effort. If the range of production values was not originally computed, the estimator would not have a "feel" for how much he could reasonably raise or lower his initial estimate.

Summary of Contractor Estimating

In summary, the steps involved in estimating earthwork outwardly appear very simple but are, in fact, deceptively complex. Each of them involves numerous factors, few of which have values known with certainty. Contractors recognizing the uncertainty associated with earthwork have chosen to account for it in a simple but fundamentally sound way by relying on their experience, intuition, and historical data. In order to put the entire foregoing section into perspective, it must be remembered that only the estimation of direct earthwork costs has been discussed. Additional components of the total highway project estimate include: (1) indirect costs for earthwork, (2) direct and indirect costs for other project activities (i.e., base course, reinforcement, paving, finishing, structures, signs, drainage, lighting, and marking), (3) possible unbalancing of certain bid items to increase profit and/or cash flow, and (4) various bidding strategies that might be adopted to increase the likelihood of being awarded projects under competitive bidding practice. It should be pointed out that the estimates included in item two above, while they contain some uncertainty, do not exhibit the variability associated with earthwork estimating. Thus, while earthwork estimating offers perhaps the greatest challenge to highway construction, it is, by no means, the sole component that determines the resultant award and profitability of a highway project.

PennDOT Estimating

Contact with two PennDOT Districts has revealed that earthwork estimates are usually prepared by consultants under contract with PennDOT. While the district office maintains project control and review/approval authority, limited manpower prevents involvement in detailed estimating for the majority of the earthwork projects. Regardless of whether the estimate is prepared by a consultant or PennDOT district engineers, however, it appears that the following procedures are usually followed:

1. Determination of quantities (including adjustment for swell/shrinkage)
2. Determination of cut/fill distribution
3. Determination of fleet costs
4. Determination of fleet productivity
5. Determination of project unit cost.

Each of the above steps are similar to those used by contractors since the end result, a unit cost for earthwork, is the objective in both cases. The major differences, which occur in steps 1, 3, and 4, are discussed below.

The determination of quantities (step 1) is made without the benefit of the field drilling that most contractors conduct. Instead, each PennDOT district relies on the opinion of either the consultant preparing the estimate or their own in-house geotechnical staff. In either case, the estimate of rock quantity is based on: (1) previous experience with earthwork jobs in the same geographic area and, (2) available boring and soils data. It is interesting to note that Gates and Scarpa (1969) proposed a method for determining earthwork quantities using random sampling, but it appears to be more applicable to mass earthwork projects, such as shopping centers and housing developments, rather than highway construction. Since the available information is usually general in nature, the rock quantity is defined only to the extent of being a certain percentage of the total quantity of cut. For example, if the project requires 1 million cy of cut and the consultant (or geotechnical staff) estimates twenty percent rock, the estimate would be completed as if exactly 800,000 cy were earth and 200,000 cy were rock (an 80/20 earth/rock split) existed.

The question can be raised as to why PennDOT does not conduct field drilling to more closely define the rock quantity. Two obvious answers are: (1) field drilling is costly and not worth the expense for PennDOT and, (2) the quantity of rock present is not a major concern to PennDOT since the Class 1 Excavation bid item covers any earth/rock composition. These two explanations, while they seem feasible and logical, do not diminish the importance to both PennDOT and the contractor of accurately estimating the relative quantities of soil and rock that are to be excavated. While the rationale for a field drilling program has been addressed earlier in the section on Contractor Estimating Methods, the second plausible explanation mentioned above merits further comment. Although the rock quantity does not directly affect PennDOT costs as it does contractor costs, it does affect the total estimated project cost. The accuracy of this cost is a major PennDOT concern because certain statutory constraints apply with respect to state and federal funding levels and this amount is impinged upon by each project estimate. Thus, while at first glance, the determination of rock quantity by PennDOT might seem inconsequential, it is a significant factor that influences their total allowable construction program for a given fiscal period.

The determination of fleet costs (step 3) represents the next difference between PennDOT and contractor estimating methods. While contractors rely on their own experience and historical data to determine their fleet costs, PennDOT must try to anticipate the fleets that will be used by the contractor. This is a problem because, if PennDOT estimators are not familiar with a contractor, they can only guess about the fleet composition. PennDOT now uses the _Cost Reference Guide For Construction Equipment_ (published annually by Dataquest of Palo Alto, Ca.) to estimate fleet costs. This guide summarizes equipment costs nationally, by region, and is based on historical data consisting of contractor-owned equipment costs. Formerly, a catalog listing only rental costs _(Blue Book)_ was used for estimating. PennDOT officals, after review of recent contract bid data, have reported that the switch to the _Cost Reference Guide For Construction Equipment_ has resulted in more "representative contractor costs" and hence better PennDOT estimates.

Fleet productivity (step 4) is determined by PennDOT through the use of historical data maintained by each district. In some cases, this data represents a combination of productivity values recorded by PennDOT field inspectors and those obtained from estimating guides. Since the field data covers several different contractors and was probably recorded by different inspectors, the expected variation in productivity data is greater than that of a single contractor maintaining a productivity history. However, since the low bidder is not known at time of estimate preparation, further research is needed before any conclusions can be inferred about the accuracy of determining productivity in this manner.

Summary

This chapter has discussed the most commonly used methods of preparing earthwork estimates. It began with a brief description of estimating guides and then explained a computerized system, SEMCAP, which was patterned after equipment performance handbooks. The typical contractor method of estimating, based on interviews with six Pennslyvania earthwork contractors, was then presented. Finally, the estimating approach used by PennDOT was described.

All of the estimating techniques discussed in this chapter are deterministic. The next chapter focuses on the subjects of Uncertainty and Probabilistic Estimating as applied to earthwork projects.

CHAPTER FOUR

UNCERTAINTY AND PROBABILISTIC EARTHWORK ESTIMATING

This chapter discusses the following two topics related to earthwork estimating: (1) Uncertainty, and (2) Probabilistic Estimating. The first section on Uncertainty explains, in a qualitative manner, the background of probabilisitic estimating. The second section on Probabilistic Estimating covers the commonly used probability distributions and the probabilistic models proposed for estimating the rock quantities and the cost elements.

Uncertainty in Earthwork Estimating

Uncertainty plays an important role in earthwork estimating. This section begins by considering the nature of uncertainty and then cites the common types of estimating errors. Next, the topic of risk is addressed along with how it relates to probabilistic estimating. Finally, the impact of human behavior on estimating and its relationship to uncertainty is discussed.

The Nature of Uncertainty

First, it is necessary to define the context in which the word "uncertainty" is used. Those involved in the management science area, for instance, consider "Decisions Under Uncertainty" as a general category of decision-making methodology and define it as "decisions whose outcomes are affected by conditions outside the decision maker's control, with the probabilities of occurrence of those conditions not known at all" (Cleland and Kocaoglu, 1981:303). While earthwork estimating involves decision making which is affected by conditions outside the decison maker's control, it is still possible, based on historical data, to assign probabilities of occurrence and, therefore, does not fall into the category of "Decisions Under Uncertainty" defined above. The uncertainty addressed here is that which relates to the variability inherent in every estimate. If one had perfect knowledge, an "estimate" would not be required since actual costs would be known in advance. Obviously, perfect knowledge is not possible nor is it possible to predict the future. In a sense then, as suggested by Schremp (1978), uncertainty can be viewed as a measure of a lack of knowledge. Schremp (122) goes on to state that:

> Lack of knowledge may consist of the nonavailabilty of current information due to a lack of an effort to find it, an inability due to time, cost, etc., to obtain it or a failure due to a deficiency in education, organization or theory to perceive it when it is available...The element of uncertainty and its effective management is the crux of all estimating and contains both its opportunities and Achille's Heel.

Types of Uncertainty

According to Ostwald (1974), uncertainties exist under two general categories: (1) long-term, and (2) statistical. Ang and Tang (1975) suggest similar categories but refer to them as: (1) natural phenomena, and (2) parameter estimation. In both classifications, the first category pertains to the state of the world or nature and, in the construction context, includes items that influence costs, such as weather, wage and price escalation, labor productivity, soil conditions, political and economic flucuations, construction technology, maintenance technology, material and equipment availability, construction delays, supervision policies, and construction methods. The second category refers to prediction errors and includes inaccuracies in the estimation of the parameters, the choice of frequency distribution(s), and the model or its assumptions.

Spooner (1974:65-66) suggests a third category for uncertainty that he labels as "unpredictable uncertainties which are qualitatively detectable, but not enough information exists to assess the risk quantitatively." He goes on to list examples of unpredictable events, such as "wildcat labor disputes, contract conditions requiring action at the discretion of the owner, contract litigation, and subcontractor default." Since these types of uncertainties cannot be quantified, they are usually included in the estimate only indirectly as part of the contingency markup. This category will not, however, be discussed further in this paper.

Estimation Error

Due to the inherent uncertainties associated with estimating, it is a recognized fact that errors or deviations will, undoubtedly, occur between estimated and actual cost elements. The estimator's goal, of course, is to minimize the disparity between estimated and actual costs so that the bid price is low enough to obtain the contract and yet high enough to allow for some margin of profit. The following paragraph discusses items pertaining to a unit-price earthmoving-type project and is based on a more general study conducted by Neil (1978).

Items of Responsibility. The "items of responsibility" in a contract often pose problems even if detailed plans, specifications, general conditions, supplementary conditions, and other documents are incorporated into the contract. Naturally, all of these documents potentially have cost implications for the contractor and yet it is usually only the plans and specifications that are given any attention during the estimating period. Many state highway departments have standard specifications that are referenced in all projects with only the special or unusual items explicitly described. Contractors, therefore, must be intimately familiar with the standard specifications in order to properly account for all cost items in their estimate. As an example, consider the work category entitled Class 1 excavation as defined in PennDOT Specifications, Section 203 (1983:82):

> Class 1 Excavation...will include the placement of excavated material in the embankment areas; the removal, storing, and rehandling, as required, for the placement of suitable material below subgrade elevation; the satisfactory disposal of all unsuitable and surplus materials: the furnishing of all materials, equipment, tools, labor, and work incident thereto; and shall also include bracing and shoring, and the bailing and/or pumping of water.

If a contractor were to estimate, bid, and be awarded a PennDOT highway project without understanding the definition of Class 1 Excavation, it is quite likely that he would sustain a significant loss. The reason is that there are several requirements (i.e., compaction, dewatering, rock excavation, rehandling, disposal, storage, etc.) that are not normally considered as part of excavation unless one has read the specifications or has had experience on a previous PennDOT highway project. Another example of implied requirements stems from Environmental Protection Agency (EPA) regulations. Contractors must insure that construction proceeds and is completed with minimal impact on the environment. Thus, items, such as noise and dust control, controlled disposal areas, and stream re-routing, can have significant cost implications and should be included in the estimate.

Quantity Take-off. Determination of quantities is always an item of importance in estimating but it takes on a unique meaning for Class 1 Excavation. The problem is in the determination of the rock quantity to be excavated. The total quantity of cut is normally owner-determined by photogrammetric techniques and is sufficiently accurate for unit-price contracts since some deviation in quantities is expected. Since Class 1 Excavation payments, as noted earlier, are not based on the type of material excavated, the contractor bears the burden of determining the earth/rock composition of cuts. The cost implications of rock versus earth excavation are obvious. Also, associated with this problem of quantity determination, is the question of availability of suitable materials. If, for instance, excavated materials are unsuitable for embankment, the contractor is normally required to dispose of these materials without additonal compensation.

Work Methods. The discrepancy between the work methods assumed for estimating and those actually used on the job are a common source of estimating error. In estimating an earthwork project, the estimator must choose among various combinations of equipment crews. Normally, there is a trade-off between daily costs for labor and equipment and the time period needed to complete the earthwork. The estimator must rely on his experience, consider the availability of labor and equipment resources, consider the local construction period and the required completion date of the project. Regardless of the effort and care that have gone into the estimate, the actual work methods usually deviate from those assumed by the estimator because of a multitude of factors that impact a construction project and which could not possibly be foreseen.

Labor Cost. Labor cost is an item that can also cause estimating error in two ways -- wage rates and labor productivity. The wage rates are relatively constant over a short period but can change dramatically over the typical 2- to 3-year duration for a large highway project. Labor productivity is more variable than wage rates and, hence, presents more of a problem to the estimator. Since earthwork is an equipment-intensive rather than labor-intensive type of operation, equipment productivity will be emphasized in this study while acknowledging that labor productivity also has an impact when one considers the equipment operators.

Equipment Cost. Equipment cost, like labor cost, has two components -- cost and productivity -- that must be considered. The equipment owning and operating cost is, perhaps, the easiest parameter to estimate. If the contractor has maintained accurate records, there will be minimal fluctuation in the average owning and operating cost for each category of equipment. Equipment productivity, however, is a major concern because of the number of factors that influence it. As pointed out earlier, the operator, based on his experience, ability, and attitude affects equipment productivity. The weather, type of soil, haul roads, accessibility, location of project site, and equipment condition are factors that also influence equipment productivity. Estimators usually consider a range of productivity values but ultimately select a single value. The deviation of the actual from the estimated productivity can be rather extreme and affect not only the contractor's costs but the scheduled project completion date as well.

Unknown Site Conditions. Unknown site conditions are a concern in all Class 1 excavation projects because, as previously explained, there is a single price for excavation, regardless of the material. In additon, conditions, such as a high water table, access difficulties, hidden underground utility lines, and restricted working areas, can seriously hinder progress and increase the contractor's costs. Although there is no way to insure against unknown site conditions, most successful earthwork contractors conduct an extensive site visit, drill test holes, and thoroughly study the plans and related documents before submitting a bid.

Area Adaptation. Area adaptation applies to those contractors who work in several geographic areas. In such cases, the estimator must apply factors to compensate for differing wage rates, labor and equipment productivities, equipment costs, permits, and construction periods allowed by the weather. Highway contractors must also consider the availability of materials if the project is a borrow rather than a waste type. Contractors familiar with an area have distinct advantages in that they can generally predict the quantity of rock to be removed more accurately, they have better knowledge of local subcontractors and equipment suppliers, and can rely on their historical data from previous projects in the same local area.

Mistakes and Errors of Omission. The foregoing paragraphs were limited to estimating errors that result from uncertainty. In order to complete this discussion, however, it should be mentioned that estimating error also results from two other sources -- mistakes and errors of omission or blunders. Mistakes, such as an arithmetic one or a misplaced decimal point, commonly occur, but are often discovered by checking or by requiring an independent estimate. Errors of omission result through ignorance or inadvertentness. Examples of these are "failure to recognize material price breaks, the omission of cost items, and overlooking a planned contractual increase in direct labor cost" (Ostwald, 1974:5). The only way to prevent these errors of omission is to have competent management policies and effective estimating practices.

Risk

The previous sections of this chapter discussed uncertainty and the estimation errors that result from uncertainty. Risk, defined as "the possibility of suffering harm or loss," originates from uncertainty. Without uncertainty there would be no risk. Contractors are faced with a great deal of risk due to the uncertainties already discussed as well as many others outside the scope of this study. While contractors generally recognize risk, it is difficult, if not impossible, to completely account for it. The most common method of attempting to handle risk is by adding a contingency to the bid. After the estimator prices all items of the project, management, usually along with the estimator, tries to collectively evaluate and incorporate all the uncertainties associated with the project and arrive at a contingency percentage. The major problem with this approach is that it is virtually impossible to subjectively evaluate the impact of all the uncertainties affecting a large project. The only logical way to handle risk is through the use of probability. The next chapter covers the subject of probability as it pertains to earthwork estimating. Before considering the mathematics of probability, however, it may be helpful to reflect on the psychological or human elements of uncertainty.

Human Behavior and Uncertainty

Psychologists have studied the problem of decision making under uncertainty. The work of Tversky and Kahneman (1974:1129) has shown that "people rely on a limited number of heuristic principles which reduce the complex tasks of assessing probabilities and predicting values to simpler judgemental operations." While these heuristics are helpful, they sometimes lead to biases and other systematic errors. Anyone using probabilistic models, such as those described later in this paper, should be aware of these biases and their impact on judgement. Tversky and Kahneman

(1974) described three heuristics that people use to assess probabilities and predict values: (1) Representativeness, (2) Availability, and (3) Adjustment and Anchoring. Representativeness is used when people are asked to judge the probability that an object or event belongs to a certain class or process. Availability is used when people are asked to assess the frequency of a class or the possibility of a particular occurence. Adjustment and Anchoring are used in numerical predictions when a relevant value is available. Since the topic of estimating deals with numbers, Adjustment and Anchoring is perhaps the most significant heuristic and, as a result, will be explained in more detail.

In most cases, estimates are made by initially considering some starting value and then adjusting this value based on specific factors, such as experience. Tversky and Kahneman, however, have found that such a heuristic causes estimating errors. They report that different starting points yield different estimates that are biased toward the starting points. The implications of this phenomenon for estimators is significant, especially if subjective three-value estimates are used. Tversky and Kahneman (1974:1129) found that "subjects state overly narrow confidence intervals which reflect more certainty than is justified by their knowledge about the assessed quantities." Thus in a three-value estimate, the most probable value serves as a psychological anchor and restricts the range, resulting in a subjective probability distribution that is distorted. A suggested method of minimizing this bias, proposed by Tversky and Kahneman, is to form estimates based on the tenth and ninetieth percentiles (or pessimistic and optimistic values) instead of a most probable or median value.

The biases inherent in judgement under uncertainty affect experts as well as neophytes. Although such errors cannot be completely eliminated, they can be controlled. The estimator who recognizes and accepts the fact that biases are a natural part of human behavior will have more confidence in his judgement and produce better estimates of uncertain quantities.

Probabilistic Estimating

The previous section discussed uncertainty in estimating and mentioned that probability is a tool used to handle uncertainty by seeking to quantify the risk. This section describes what is meant by probabilistic estimating, discusses major probabilistic estimating methodologies, and explains the three probabilistic models that are used in the proposed system, which is explained in Chapter Six.

Definition

The traditional estimating approach uses a single value for each line item and, after addition of all items, arrives at a single value that represents the unit cost or total cost for the project. Such a method is deterministic, in that, it assumes conditions of certainty. The probability that the actual cost equals the estimated cost is extremely small, but the probability that the estimated cost will be within a limited range around the actual cost is significant. In effect, the single value estimated cost is bracketed for each cost element. Another approach is to consider the actual cost as a random variable and use a mathematical formulation. (A random variable is defined as a numerical-valued function of the outcomes of a sample of data [Ostwald, 1974]).

For the purposes of this thesis, a probabilistic estimate is defined as one consisting of a combination of both deterministic and random cost elements. It is assumed that the random cost elements can be described by a continuous, unimodal, non-negative, real-valued probability density function (pdf) (Diekmann, 1983).

Probability Distributions

In the classical approach to the estimation of parameters, the mean and variance are the main descriptors of a random variable. It becomes necessary then to adopt a method for determining the mean and variance and to select an appropriate distribution for the cost elements.

The traditional method of determining the mean and variance is by assuming that a sample set of observational data can be used to determine the parameters of the underlying population. In earthwork estimating, however, a general lack of data, due to the many uncertainties, prevents one from effectively using the traditional approach.

Spooner (1974:72-73) described the characteristics of the pdf when there is a lack of data:

> 1. Limits -- On any estimate, upper and lower limits exist beyond which the estimator is relatively certain that no values will occur. The actual placement of these extreme limits may be uncertain but this uncertainty will not be included in subsequent developments since it is considered of secondary importance.
>
> 2. Continuity -- There is no reason to believe that the pdf is discontinuous.
>
> 3. Convexity -- It will be assumed that the probability of occurrence of an event decreases as the upper and lower limits are approached. In addition it will be assumed that the distribution is unimodal.
>
> 4. Skewness -- Since actual costs have a greater freedom to be higher than lower with respect to the estimate, skewness to the right should be expected.

The normal, beta, log-normal, and triangular distributions all fit the above criteria. The choice of distribution is important because the values of the resulting means and variances will be biased with respect to a different choice. Law and Kelton (1981) and Spooner (1974) suggest the use of a triangular distribution as a simple approach under conditions of uncertainty. The beta distribution is perhaps the most flexible and, depending upon the choice of shape factors, it can be made to take on a wide assortment of shapes. The normal distribution is the most commonly used, especially when modeling construction material characteristics, such as the compressive strength of concrete or the bearing strength of soil. The log-normal distribution is sometimes used as well since values can be obtained from the table of standard normal probabilities. The proposed estimating system, discussed in later chapters, will make use of the beta, double triangular, and normal distributions. Since the normal distribution is so common, the remainder of this section will only address the important properties of the beta and double triangular distributions.

Beta Distribution. Figure 4-1 (Ang and Tang, 1975) depicts a few of the possible shapes of the beta pdf resulting from the selected values of the parameters q and r. The density function is defined as:

$$f_X(x) = \left(\frac{1}{B(q,r)}\right)\frac{(x-a)^{q-1}(b-x)^{r-1}}{(b-a)^{q+r-1}} \qquad a \le x \le b \qquad (3)$$

$$= 0 \quad \text{elsewhere}$$

where,

a and b are finite limits

q and r are shape parameters

B(q,r) is the beta function

defined as,

$$B(q,r) = \int_0^1 x^{q-1}(1-x)^{r-1}dx \qquad (4)$$

The mean and variance are:

$$E(X) = a + \frac{q}{q+r}(b-a) \qquad (5)$$

$$\mathrm{Var}(X) = \frac{qr}{(q+r)^2(q+r+1)}(b-a)^2 \qquad (6)$$

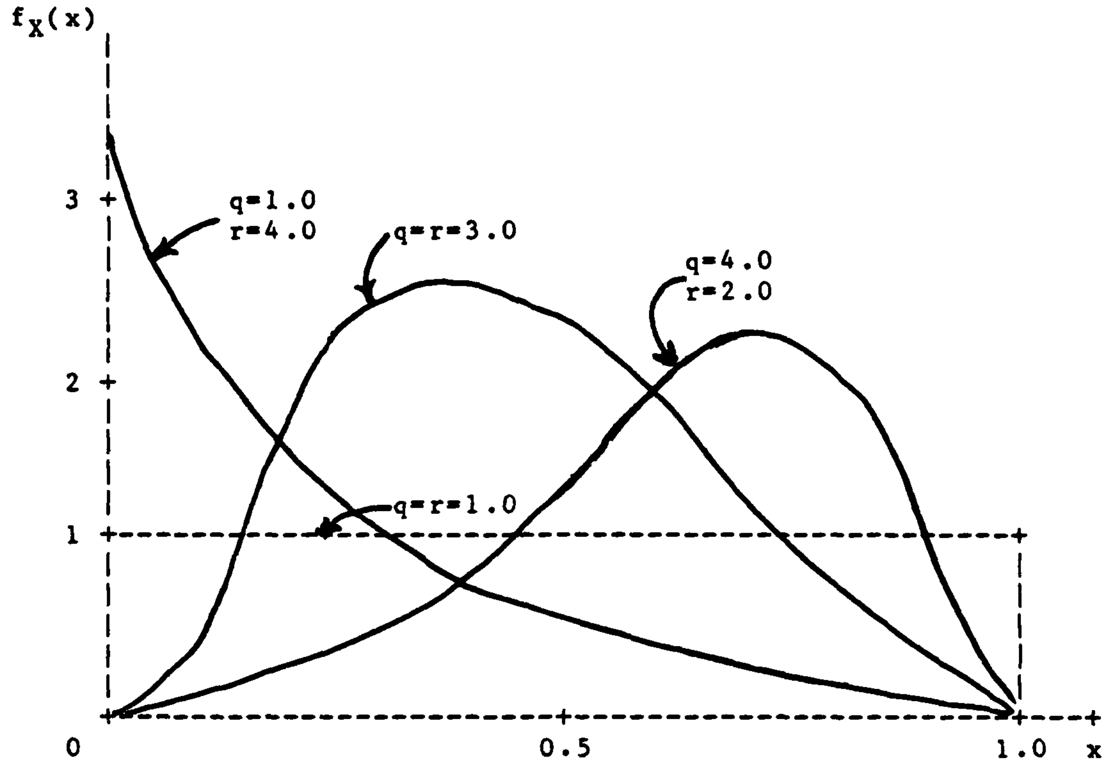


FIGURE 4-1 Standard Beta PDF (Ang and Tang, 1974:130)

A modified version of the beta distribution is used for Program Evaluation and Review Technique (PERT) estimates. As applied here, however, it requires the estimator to make a pessimistic (highest cost), a most likely, and an optimistic (lowest cost) estimate for each cost element. Figure 4-2 ilustrates the relative location of the three estimates for a hypothetical cost element. The mean and variance are approximated as:

$$E(C_i) = \frac{L+4M+H}{6} \tag{7}$$

$$Var(C_i) = \frac{(H-L)^2}{36} \tag{8}$$

where $E(C_i)$ = mean cost of element i

L = lowest cost

M = most likely cost

H = highest cost

$Var(C_i)$ = variance of cost element i

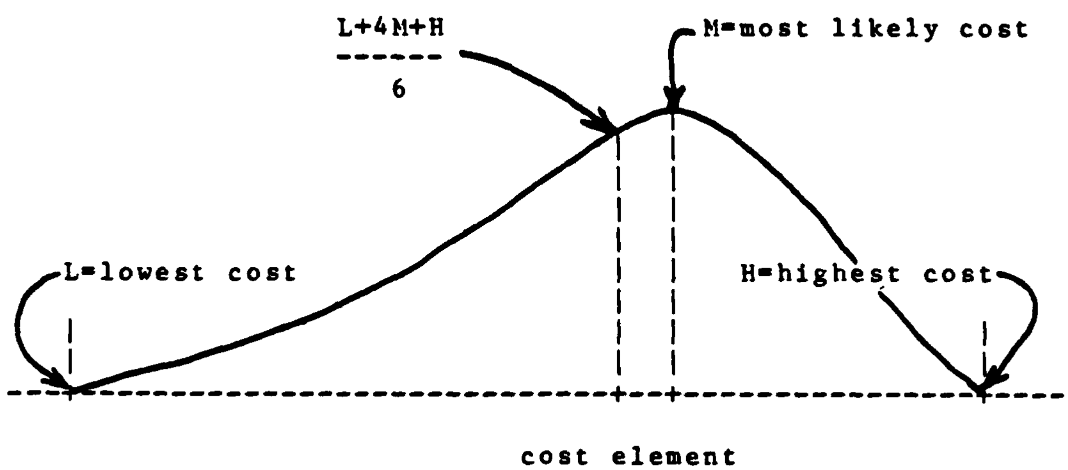


FIGURE 4-2 Location of Estimates For PERT-Based Beta Distribution (Ostwald, 1974:182)

<u>Double Triangular Distribution</u>. Although the beta distribution has the inherent flexibility to adapt to many shapes, it is computationally awkward. Consequently,

researchers have commonly used distributions, such as the double triangular which are much easier to program for computer applications and yet provide an acceptable alternative to the beta for problems involving uncertainty. The double triangular distribution uses a parameter, P, to account for user confidence and to more closely resemble the beta distribution. The double triangular distribution will be described in more detail in the forthcoming section on "Replication of Cost Elements".

Figure 4-3 indicates a double triangular distribution with the specified parameters a, b, u, and P. The density function is defined as:

$$f_X(x) = \frac{2}{b-a}\,\frac{(x-a)}{(u-a)} \quad \text{for } a \leq x \leq u \tag{9}$$

$$= \frac{2}{b-a}\,\frac{(b-x)}{(b-u)} \quad \text{for } u \leq x \leq b$$

The mean and variance are defined as:

$$E(X) = \frac{1}{3}(a+b+u) \tag{10}$$

$$Var(X) = \frac{1}{18}(a^2+b^2+c^2-ab-au-bu) \tag{11}$$

Spooner (1974:73) indicates that the variance can be approximated, with only slight error, by the following expression:

$$Var(X) = \frac{1}{20}(b-a)^2 \tag{12}$$

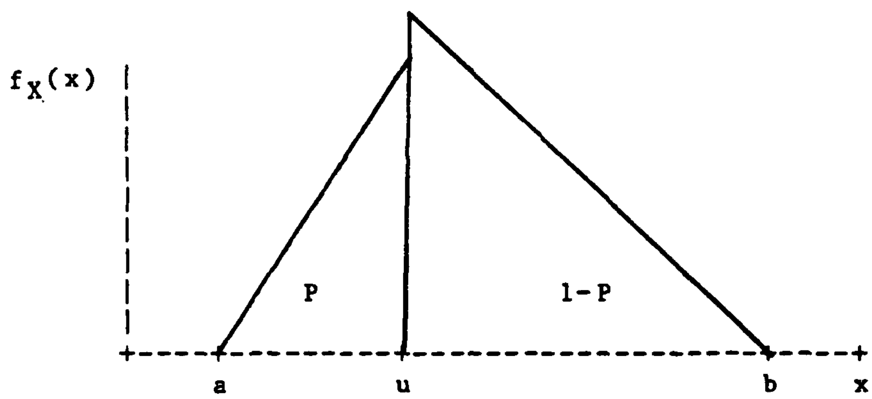


FIGURE 4-3 Location of Estimates For Double Triangular Distribution

Proposed Earthwork Estimating Models

This section describes the three probabilistic models that are used in the proposed estimating system. First, the normal distribution is used to model the quantity of rock in cut areas. Next, the beta distribution is used to model the uncertain cost elements. Finally, a double triangular distribution is used to replicate the cost elements contained in the linear programming solution that is described in the next chapter. Note that the integration of these models in the proposed estimating system will be discussed in Chapter Six.

Rock Quantity. The determination of the quantity of rock in cut areas presents a unique modeling problem. The actual amount of rock is a fixed quantity but one that is unknown, and hence uncertain, until the excavation is completed. The estimator must rely on factors, such as boring data, test drilling data, and experience, to estimate the quantity of rock in a cut section. Depending on the amount of information available, the estimator may be able to plot the rock lines on cross-section drawings as was shown in Figure 3-1. The probability of the estimated quantities being exactly equal to the actual quantities is extremely small, however, the probability that they will be within a range around the actual quantities is significant.

An assumption was made that the estimated quantity of rock in any given cut follows a normal distribution. What this means is that, if an estimator repeatedly calculates the quantity of rock for a particular cut (perhaps over a period of time or with differing amounts of available information), his estimates, if plotted, would follow a normal distribution. While conclusive proof to substantiate this assumption is lacking, the normal distribution has been widely used to model similar natural phenomena, such as the quantity of rainfall, reservoir demand, and soil conditions.

The mean, μ , and the standard deviation, σ , are the parameters that describe the normal distribution. A normal distribution with parameters $\mu = 0$ and $\sigma = 1.0$ is known as the standard normal distribution and is denoted as N(0,1). The significance of the standard normal distribution is that values for this distribution have been tabulated and are readily available. One only has to convert a variable into a normalized version and the normalized variable will also be normally distributed with zero mean and a standard deviation of one. If the quantity of rock in a particular cut has a mean value of $E(b_i)$ and a standard deviation of b_i, the normalized variable would be expressed as:

$$Z = \frac{b_i - E(b_i)}{\sigma b_i} = \text{--> Normal } (0,1). \qquad (13)$$

where b_i = random variable representing the quantity of rock in Section i

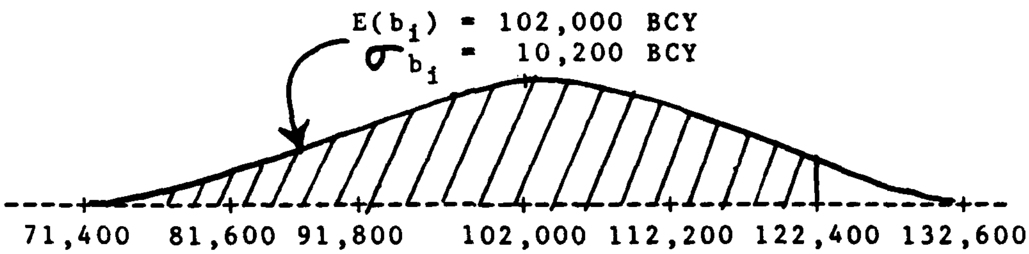
$E(b_i)$ = estimated mean value of quantity of rock in Section i

σb_i = estimated standard deviation of the quantity of rock in Section i

Z = a normally distributed random variable with zero mean and standard deviation of one.

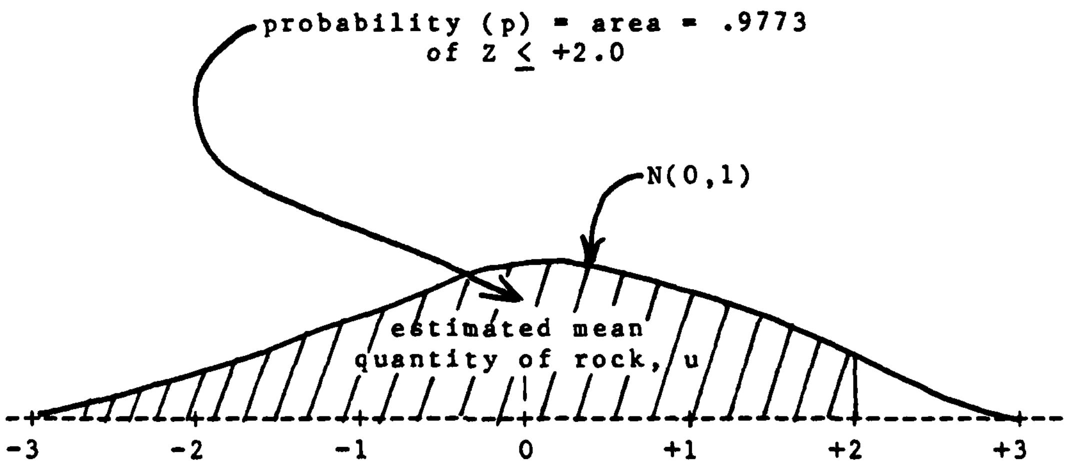
The values of Z are tabulated and can be used to determine areas under the normal curve. These areas provide the probability that the random variable Z takes on values less than or equal to a number of standard deviations to the left or to the right of the mean (Aguilar, 1973). As an example, the equation $P(Z \leq +2.0) = 0.9773$ means that there is a probability of 97.73 percent that the value of the estimated quantity of rock lies between $-\infty$ and two standard deviations to the right of the estimated mean. Figure 4-4 illustrates this example using data from Table 3-2. The quantity of excavation between stations 10+00 and 20+00, for example, is 340,000 CCY (408,000 BCY). The estimator has

Probability that $V \leq 102{,}000 + 2(10{,}200)$
or $V \leq 122{,}400 = 97.73\%$



Estimated Quantity of Rock (BCY), V
(a)

$$Z = \frac{b_i - E(b_i)}{\sigma_{b_i}} = \frac{122{,}400 - 102{,}000}{10{,}200} = +2.0$$



Standard Deviations,
(b)

FIGURE 4-4 Illustration of Standard Normal Density Function determined that there is 20- to 30-percent rock in this cut. He can estimate the mean and standard deviation (Ott,1977:37) as follows:

$$\mu = \frac{20+30}{2} \div 100 \times 408{,}000 \qquad \sigma = (30-20) \div 100 \times \frac{408{,}000}{4}$$

$$\mu = 102{,}000 \text{ BCY Rock} \qquad \sigma = 10{,}200 \text{ BCY Rock}$$

The same technique is followed to estimate the rock quantity in each of the cut sections. Chapter Five describes how the mean and standard deviation are used to formulate the chance constraints for the rock quantity.

Cost Elements. The general form of the cost equation for earthwork can be represented as follows (Stark and Mayer, 1983:37):

$$C_T = C_e + (C_h)(d) + C_c \tag{14}$$

where C_T = total unit cost for an element ($/BCY)

C_e = unit cost for excavation and loading ($/BCY)

C_h = unit cost for hauling per grading section ($/BCY -- grading section)

d = haul distance in number of grading sections (grading section)

C_c = unit cost for placement and compaction ($/BCY).

Each of the four parameters associated with the total unit cost can be treated as a random variable that follows a beta distribution. A three-value estimate of the beta distribution is used to describe each random cost element and the mean and variance are calculated as follows:

$$E(C_i) = \frac{L + 4M + H}{6} \tag{15}$$

$$Var(C_i) = \frac{(H-L)^2}{36} \tag{16}$$

where the parameters are the same as those previously defined.

According to the central limit theorem, if many such independent cost elements are added together, the distribution of the sum of the cost elements and, therefore, the total cost, is approximately normal irrespective of the distributions of the individual cost elements. In equation form this can be represented as follows:

$$E(C_T) = E(C_1) + E(C_2) +...+ E(C_n) \tag{17}$$

$$Var(C_T) = Var(C_1) + Var(C_2) +...+ Var(C_n) \tag{18}$$

where $E(C_T)$ = expected total cost

$Var(C_T)$ = variance of total cost.

The $E(C_i)$ will be computed for each random cost element. These values will be used as cost coefficients in the objective function of the linear programming model that is described in the next chapter.

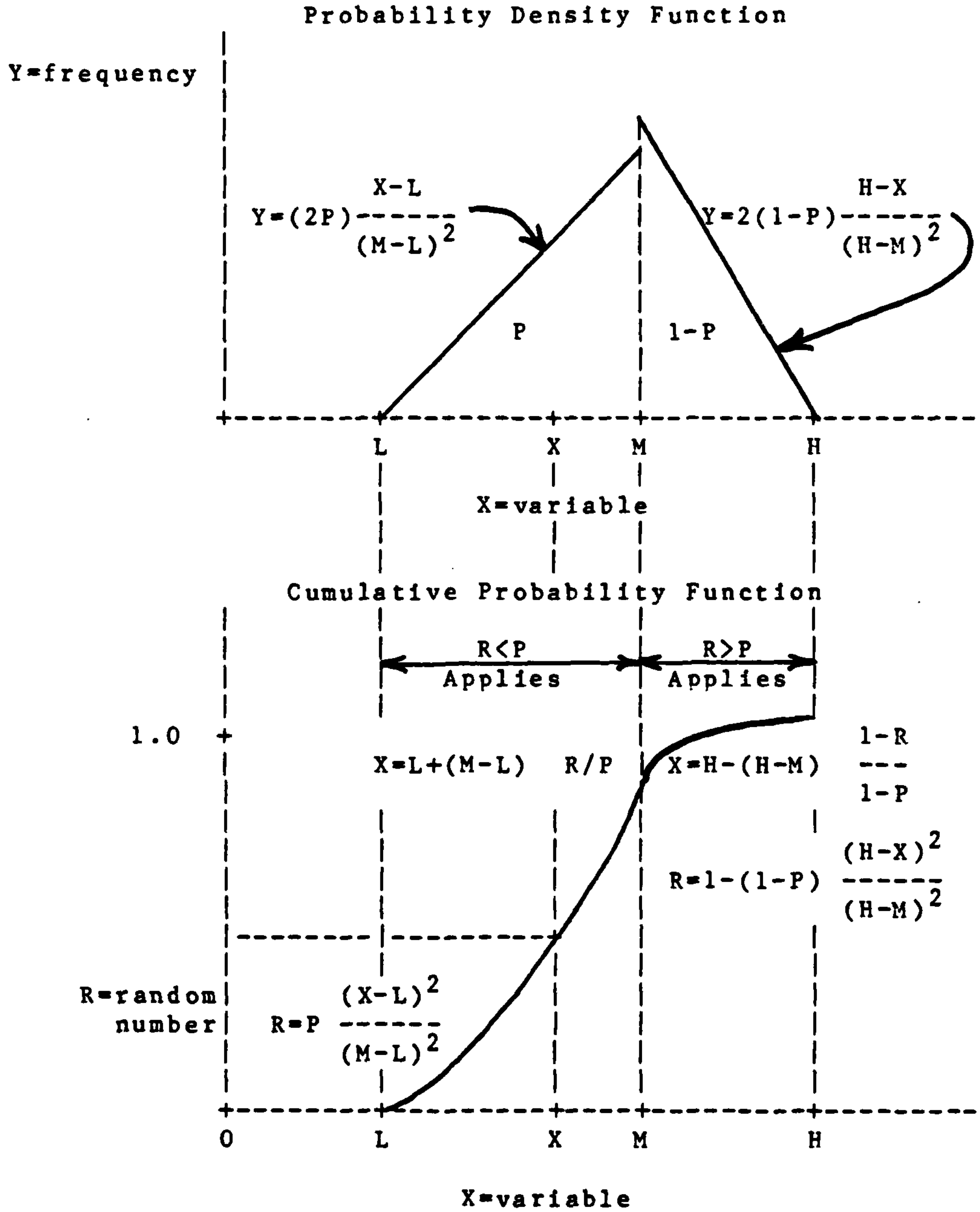
Replication of Cost Elements. A linear programming model will be used to identify those cost elements corresponding to the variables in the optimum solution. The model to be described will then be used to replicate the cost elements contained in the optimum solution. Initially, only the mean values of the cost elements, described in the last section, are used as input into the linear programming model. The purpose of replicating the cost element values is to obtain a probability distribution and cumulative probability distribution function for the total unit cost. To achieve this objective, it is necessary to simulate the cost element values through Monte Carlo Sampling and yet select samples from a distribution that is appropriate for the cost elements. The double triangular distribution proposed by Van Tetterode (1969) was selected because: (1) it provides for ease of computation, (2) it allows the use of a confidence factor, and (3) it enables the user to evaluate both the upper- and lower-side risk.

Figure 4-5 illustrates the double triangular distribution and presents the derived equations which are necessary in order to utilize it on the computer.

The distribution is completely defined by the following four parameters (Van Tetterode, 1971:125):

L = lowest estimate of the variable
M = most likely estimate of the variable
H = highest estimate of the variable
P = probability of an outcome between L and M or, in other words, the area under the curve between L and M. (The total area under both triangles is equal to one.)

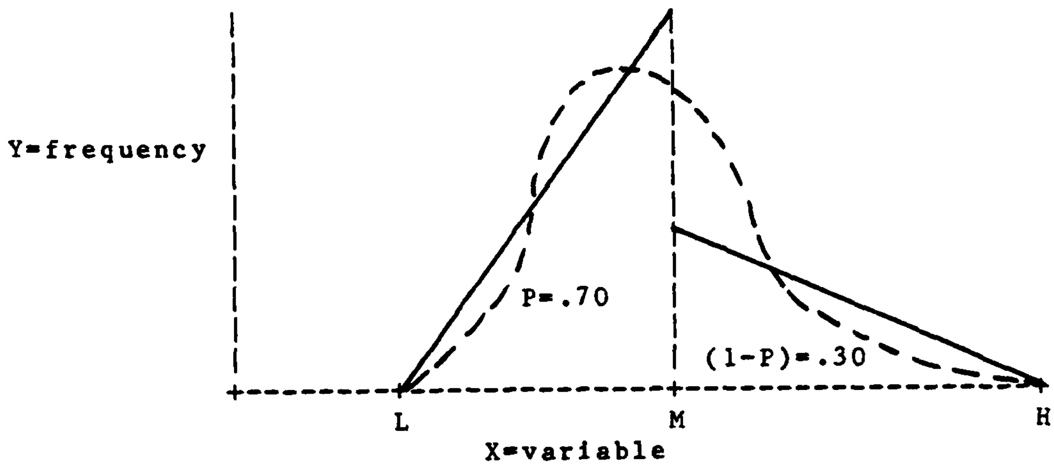
The first three parameters are the same as those used in the PERT-type beta distribution. The parameter, P, is unique to this distribution and can be viewed as a "confidence factor" by the estimator. Stated another way, the parameter P represents the probability that the most likely estimate, M, will not be exceeded. The effect of the parameter, P, on



NOTE: Refer to Appendix A for the derivation of the above equations.

FIGURE 4-5 Double Triangular Distribution (Van Tetterode, 1971:127) the distribution is to act as a built-in skewness or shape control. For example, consider Figure 4-6 which depicts two distributions differing only in the selected value of the parameter P. If a beta distribution is superimposed, as shown by dotted lines, it is evident that the top figure is skewed to the right while the bottom figure is skewed to the left. This, in turn, affects the cumulative distribution from which the random samples are drawn.

Once the four parameters for each cost element have been defined, Monte Carlo Sampling can be employed to replicate the double triangular model. The Inverse Transform Method is used to generate values from the cumulative probability curve of the double triangular distribution. This method consists of generating a random number, uniformly distributed between 0 and 1, and solving for the inverse of the cumulative probability function to obtain a "random" value. Figure 4-7 graphically illustrates the results of this procedure. The top portion of the figure represents the defined distribution based on the values of L, M, H, and P that were selected by the estimator. The lower figure is the cumulative probability curve that can be drawn from the equations for R as shown on Figure 4-5. In this example, it is assumed that .35 was selected by the random number generator (Random number generation can be accomplished manually by using a random number table or it can be computerized). In this case, the value of 1803 would be assigned to the variable for this



Note: Dotted lines represent superimposed beta distribution

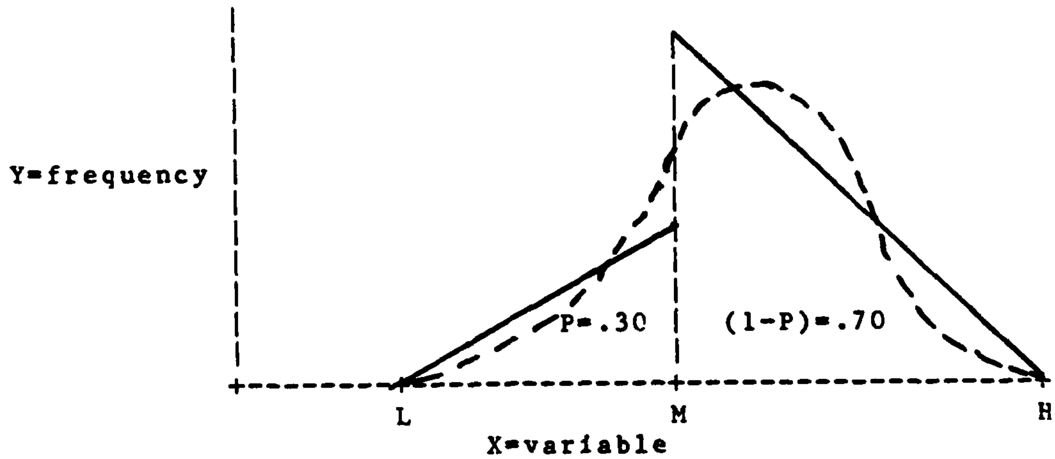


FIGURE 4-6 Illustration of the Impact of P on the Double Triangular Distribution

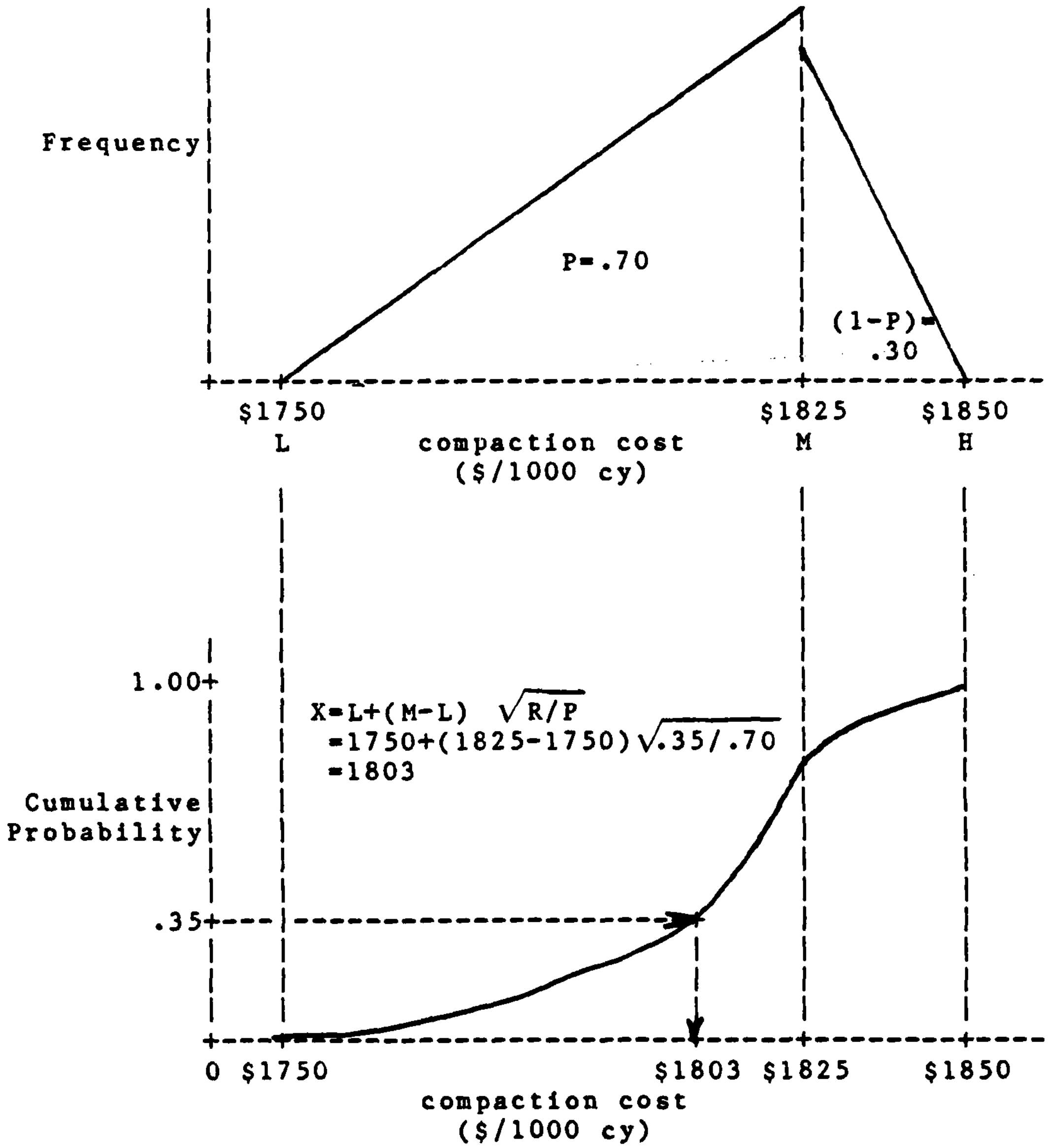


FIGURE 4-7 Graphical Representation of Inverse Transform Method of Generating Random Values

replication. Note that future replications could result in any value between 1750 and 1850. The value of 1803 in the last example can, of course, be computed analytically. For this example, the following equation appearing in Figure 4-5 (corresponding to the $R < P$ case) would apply:

$$X = L + (M-L)\sqrt{R/P} \tag{19}$$

and substituting the values of the example,

$$\begin{aligned} X &= 1750 + (1825-1750)\sqrt{.35/.70} \\ &= 1750 + (75)(.707) \\ &= 1803 \quad \text{(Same value as graphical solution).} \end{aligned}$$

Each of the random cost elements identified by the linear programming optimization would be replicated using the technique described. The number of replications required will be discussed in Chapter Seven.

Summary

The first section of this chapter discussed the subject of uncertainty by considering its nature, the types of uncertainty, and the estimation errors resulting from uncertainty. The topic of risk was briefly highlighted, followed by the examination of the human elements involved in estimating. It was concluded that probability theory is the only proven method of dealing with uncertainty and, hence, risk.

The subject of probabilistic estimating, as related to earthwork estimating, was discussed in the second section. The beta and double triangular distributions were identified as two distributions often used when prior data is not available. Proposed models for the determination of rock quantity, estimation of cost elements, and replication of cost elements were explained in detail. These models will be integrated with a linear programming optimization program to form the nucleus of the proposed estimating system.

The next chapter discusses the linear programming formulation and Chapter Six explains the proposed earthwork estimating system.

CHAPTER FIVE

LINEAR PROGRAMMING SOLUTION TO HAUL-MASS

This chapter discusses the linear programming (LP) method of solving haul-mass earthmoving problems. Since the haul-mass diagram has been the traditional technique for determining cut/fill distribution, the first part of the chapter will be devoted to this topic. Next, the LP formulation for optimizing the distribution of earthwork quantities is presented. Finally, a technique known as chance constrained programming (CCP) is described. CCP will be incorporated into the standard LP model and used to account for the uncertainty associated with rock quantities.

Haul-Mass Diagram

The haul-mass diagram is a technique that originated over seventy years ago when highway construction was in its infancy. Even so, it still remains as one of the most popular methods of approximating optimum cut and fill distribution for highway earthwork. It is necessary to understand the concept of haul-mass diagrams in order to appreciate the advantages and implications of the recently proposed technique of using LP to optimize the earthwork distribution. The following will, therefore, explain the development, the application, and the limitations of a typical haul-mass diagram.

Development

A simplified profile and haul-mass diagram is shown in Figure 5-1. Plotting the haul-mass diagram below the profile, with the same horizontal scale, helps to illustrate its relationship to the profile drawing. The vertical scale of the profile drawing is elevation (as determined by surveying information) with cut being above the base line and fill below it. In Figure 5-1, the proposed grade is assumed to be horizontal and is represented by the base line. The vertical scale of the haul-mass diagram is in cumulative cubic yards and it represents the algebraic sum of cut and fill quantities between a selected point of beginning and any station in question. The horizontal scale on both the profile and haul-mass diagram is in stations which are increments of distance, usually 100 feet as in this example. Note that 10-station increments (known as 1000-foot sections) are labeled on the horizontal scales.

Table 5-1 summarizes the information needed to prepare a haul-mass diagram for our example. Columns 2 and 3 indicate the excavation (cut) and embankment (fill), respectively, for each 1000-foot grading section. Normally this information is provided by the State Highway Department and included in the plans that are issued to contractors. Column 4 indicates the adjusted excavation volume if one is converting to embankment (fill) quantities, which are expressed in compacted cubic yards (ccy). The swell and shrinkage factors, characteristic of all soil and rock,

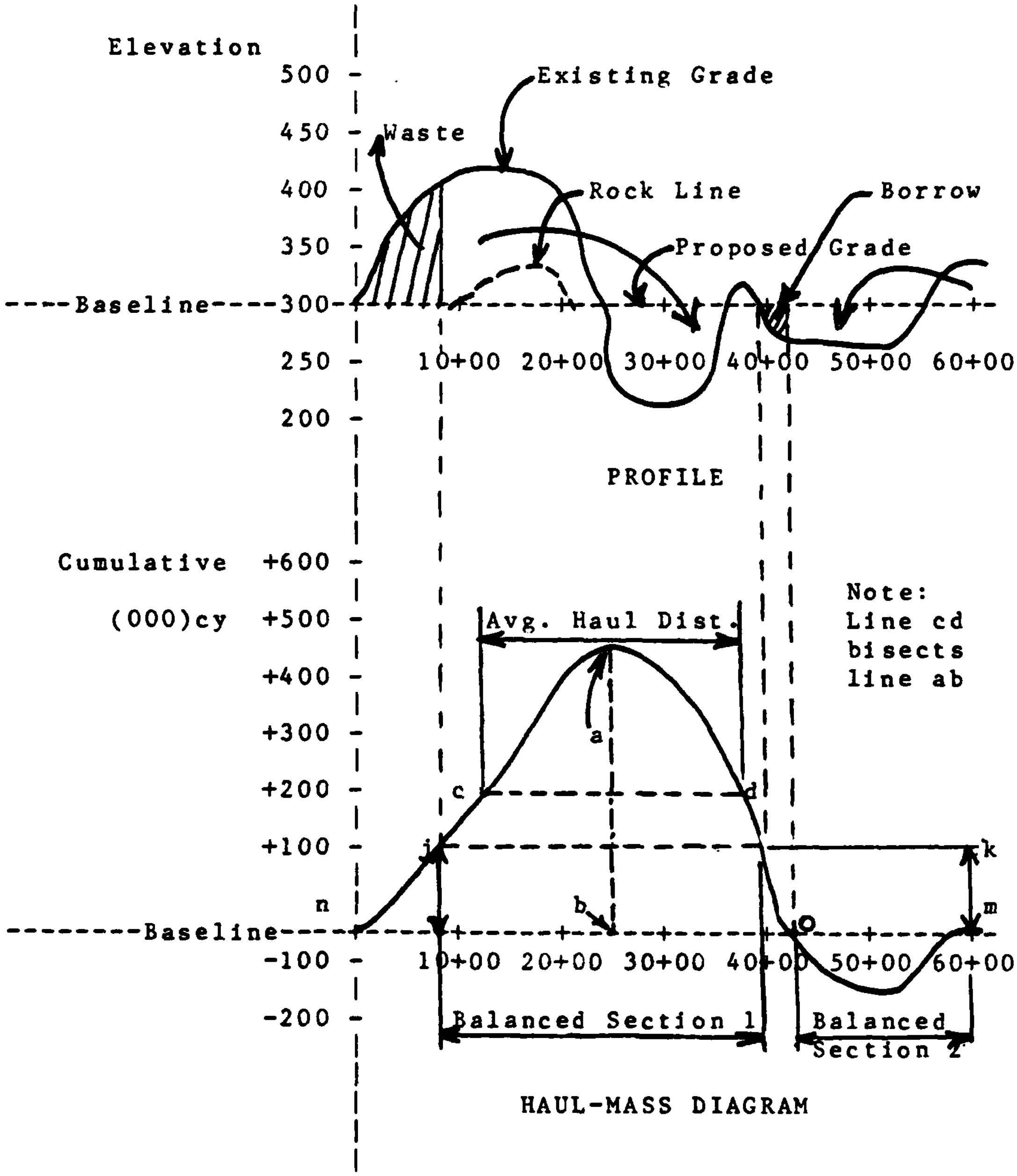


FIGURE 5-1 Simplified Profile and Haul-Mass Diagram

TABLE 5-1

Haul-Mass Diagram Data

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7
Sta.	Excav. BCY Earth(rock)	Embank. CCY	Excav. CCY Earth(rock)	Excess Embank (-)	Excess Excav. (+)	Mass Curve Ordinate
0+00-10+00	34,890	5,000	31,400	------	26,400	26,400
10+00-20+00	366,110 (8,750)	400	329,500 (10,500)	------	339,600	366,000
20+00-30+00	37,780 (7,500)	63,000	34,000 (9,000)	20,000	------	346,000
30+00-40+00	24,440 (4,170)	194,600	22,000 (5,000)	167,600	------	178,400
40+00-50+00	3,300	420,000	3,000	417,000	------	-238,600
50+00-60+00	315,110	45,000	283,600	------	238,600	0
TOTALS		728,000	728,000			

NOTES:
1. Assumed shrinkage factor is .9 (i.e., 1 cy Excav. = 1.1 cy Embank.) for earth, 1.2 for rock.
2. Excess Embank. (Col. 5) equals Col. 3 - Col. 2 if Col. 3 > Col. 4, otherwise Note 3 applies.
3. Excess Excav. (Col. 6) equals Col. 4 - Col. 3 if Col. 4 > Col. 3, otherwise Note 2 applies.
4. Col. 7 is the cumulative algebraic total of Cols. 5 and 6.
5. For purposes of clarity, only the total quantities (earth and rock) are shown in Cols. 5, 6, and 7.

require that either the cut or the fill be converted to a common basis. (Note: Swell and Shrinkage will be discussed in the following section.) In our example, the cut was converted to equivalent fill volume. If a specific project involves "freehaul" and "overhaul" items (to be discussed in the Applications Section), it may be advantageous to convert the fill to equivalent cut volume (bank cubic yards) since that is the quantity paid for in the highway contract. Columns 5 and 6 simply represent the algebraic difference between columns 3 and 4. By convention, an excess excavation is expressed as a (+) quantity and an excess embankment as a (-) quantity. Column 7, then, represents the cumulative algebraic sum of columns 5 and 6 as one proceeds from the first to the last station. Column 7, along with column 1, are the only data needed to plot a haul-mass diagram. Nichols (1969) points out that a haul-mass profile can be plotted with the data from columns 5 and 6. While such a plot is not as useful as the haul-mass diagram it may be easier to interpret by those, such as contractors, not previously exposed to haul-mass diagrams. The next section explains the definition and ramification of swell and shrinkage.

Swell and Shrinkage

Material that is excavated undergoes a change in volume and density. As material is loosened, air voids increase the volume and proportionally decrease the density. This increase over the original undisturbed volume is called

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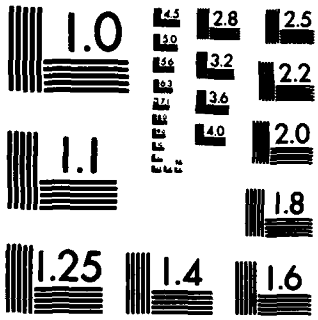

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swell and is defined as:

$$S_w = \frac{V_l - V_b}{V_b} \tag{20}$$

where S_w = swell (Note: S_w x 100 = percent swell)

V_l = loose (after excavation) volume, usually expressed in units of loose cubic yards (LCY)

V_b = bank or original undisturbed volume, usually expressed in units of bank cubic yards (BCY).

The significance of swell is that an excavation contractor must haul the loose volume which, depending on soil type, can be as much as 50 percent more than bank volume and yet he is generally paid based on the bank volume.

When soil is compacted in embankment areas it usually occupies less volume than it did in its bank state. This decrease in volume is known as shrinkage and is defined as:

$$S_h = \frac{V_b - V_c}{V_b} \tag{21}$$

where S_h = shrinkage

(Note: S_h x 100 = percent shrinkage)

V_b = bank volume

V_c = compacted volume, usually expressed in units of compacted cubic yards (CCY).

It should be noted that rock usually swells from the bank to the compacted state (i.e., compacted volume is greater than bank volume). The significance of shrinkage is that more earth material is needed for fill areas than that computed based on physical dimensions.

To summarize the effects of swell and shrinkage, Oglesby (1982:605) points out that "1 yd^3 of earth in the cut may use 1.25 yd^3 of space in the transporting vehicle, and finally occupy only 0.85-0.65 yd^3 in the embankment, depending on its original density and the amount of compaction applied."

The earthwork contractor must be aware of swell and shrinkage and take their effects into account by converting volumes to a standard reference. This also holds true for preparing a haul-mass diagram. The results achieved are bound to be inaccurate unless the volumes have been properly converted to a common volume (i.e., bank, loose, or compacted).

The volumes can be related by the swell and shrinkage factors, as shown, or they may be converted using the relative densities of the materials. Consider these basic relationship:

$$V_b B = V_l L = V_c C \qquad (22)$$

where L = Loose density

B = bank density

C = compacted density

V_l, V_b, V_c = corresponding volumes as defined earlier in equations (20) and (21).

Equation (22) can be rewritten as:

$$V_l = \frac{V_b B}{L} \quad (23) \qquad \text{and} \qquad V_c = \frac{V_b B}{C} \quad (24)$$

Equations (23) and (24) can now be used to relate swell and shrinkage to densities by substituting into the defining equations (20) and (21):

For Swell	For Shrinkage
$S_w = \dfrac{V_l - V_b}{V_b}$	$S_h = \dfrac{V_b - V_c}{V_b}$
Substituting equation (23) for V_l we have;	Substituting equation (24) for V_c we have;
$S_w = \dfrac{\dfrac{V_b B}{L} - V_b}{V_b}$	$S_h = \dfrac{V_b - \dfrac{V_b B}{C}}{V_b}$
$S_w = \dfrac{B}{L} - 1 \quad (25)$	$S_h = 1 - \dfrac{B}{C} \quad (26)$

Applications

The following major uses of the haul-mass diagram have been summarized by Horace Church (1981:17-20) as follows:

> 1. Calculating the amount of freehaul and overhaul in station yards: sometimes the units of measurement of haul are in terms of freehaul and overhaul rather than in terms of the one unit, the cubic yard, regardless of the distance moved. Freehaul is the movement of one cubic yard through a maximum distance. The maximum distance may be any length, but it is usually either 500 ft. or 1000 ft. Overhaul is the movement of one cubic yard through any distance in excess of the freehaul distance. When the freehaul-overhaul system is used for bidding, a cost and a price must be established for freehaul

and a cost and a price must be established for overhaul.

2. Making studies of the comparative costs of different schemes for hauling: these schemes generally involve the waste of fill from the cut and the borrowing of cut for the fill.

3. Determining quantities of excavation or embankment with a given length of cut or fill.

4. Determining the location of the centers of gravity of the cut and fill: these are generally determined horizontally along the centerline of the work, although they may be determined vertically by plotting a mass diagram in a vertical direction. The determination of a vertical center of gravity is rarely made.

NOTE: A station yard is defined as 1 cubic yard moved horizontally through a distance of one station (usually 100 feet).

Within PennDOT, freehaul and overhaul are not used in highway contracts. Thus, the first major reason or purpose for haul-mass diagrams is not relevant within the scope of PennDOT projects. Perhaps this explains why none of the contractors interviewed use the haul-mass diagram.

Figure 5-1 illustrates how the haul-mass diagram can be used to approximate the cut and fill centers of gravity and the average haul distance. Line ab is a vertical line drawn through the maximum ordinate of the convex loop of the haul-mass diagram. Line cd is a horizontal line which bisects line ab. Point c then approximates the center of gravity of the cut region while point d approximates the center of gravity of the fill region. The distance cd is the average haul distance for this section of the haul-mass diagram. A similar construction can be used on concave sections of the haul-mass diagram.

In the previous discussion, the base line nm was assumed to be the balance line. This means that between points n and o there is an equal volume or "balance" of cut and fill. An alternative balance line jk could also be used with the result being a quantity of excess cut material (approximately 100,000 ccy) wasted at the beginning section of the project and an equal quantity borrowed at the end section as shown on Figure 5-1. Depending on the available disposal and borrow sites, contractors can select balance lines that provide the greatest advantage. Since this study is limited to earthwork operations within Pennsylvania, the topics of freehaul and overhaul will not be discussed further. The interested reader is referred to Church (1981), Oglesby (1982), and Wright (1979).

Limitations

Stark and Mayer (1983) outlined the situations in which haul-mass and arrow allocation diagrams have limitations as follows:

1. When hauling costs are not directly proportional to the haul distance.
2. When soil characteristics vary along the roadway (particularly the percentages of swell or shrinkage).
3. When additional quantities of soil are available, or may be disposed of, at off-the-roadway sites.

To this list, the following limitations can be added:

4. A haul-mass diagram analysis does not automatically indicate optimum distribution of material.
5. The haul-mass diagram does not show the different types of material to be excavated (i.e., earth or rock).

The model formulation described later in this thesis addresses limitations 1 thru 4 but is unique by virtue of the fact that it also considers the 5th limitation. While the 5th limitation appears to be minor, it actually adds the complex factor of uncertainty, as addressed earlier, to the haul-mass problem. This limitation will be addressed in the section on Chance Constrained Programming.

Standard Linear Programming Model

Earthwork involves the following three categories of operations: (1) excavation/loading, (2) hauling, and (3) placement and compaction. As noted earlier, all three are included within the single bid item of Class 1 excavation by PennDOT. While placement and compaction costs are relatively fixed, excavation and hauling operations include numerous uncertainties that must be accounted for in the estimate. The quantity of rock to be excavated and the average production represent the major variables affecting the overall cost. As noted in Chapter Three, the haul-mass diagram or a simplified arrow diagram version of it has been

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The use of LP for minimizing earthwork costs was first suggested by Stark and Nicholls (1972) and recently expanded by Stark and Mayer (1983). Thus far, the development has been deterministic with sensitivity analysis being the only method available for studying variations in the parameters. The proposed model in this thesis seeks to account for the uncertainty of earth/rock composition within the model formulation rather than relying only on the sensitivity analysis. Before discussing the formulation for uncertainty, a brief summary of the basic deterministic form will be given.

Figure 5-2 represents the profile of a hypothetical short section of highway. The proposed grade is shown dotted and the numbered divisions represent sections that will correspond to the variable subscripts [i.e., X(2,3) represents the quantity of material to be moved from section 2 (cut) to section 3 (fill)]. The quantity of cut or fill is shown above each section.

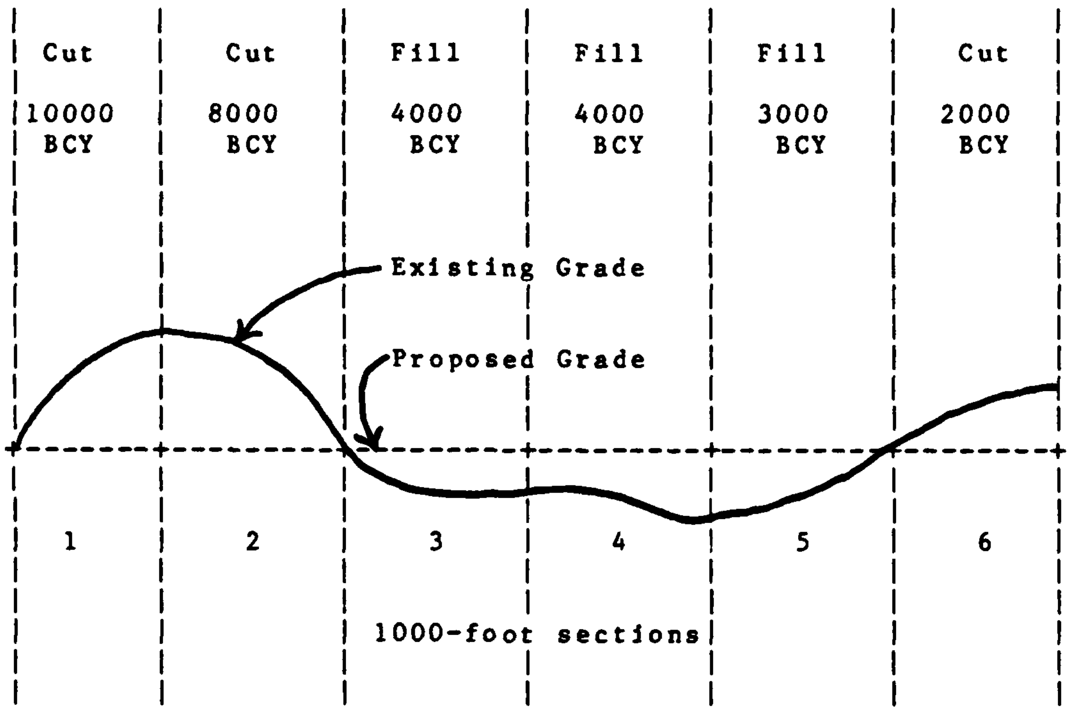

Figure 5-2 Profile of Highway

In formulating this problem, the following variables (assuming no borrow or waste locations) would appear in the objective function:

X(1,3)	X(2,3)	X(6,3)
X(1,4)	X(2,4)	X(6,4)
X(1,5)	X(2,5)	X(6,5)

Note that variables such as X(3,1) will be zero and have no logical meaning since they would indicate moving material from a fill to a cut area. Such variables should not be included in the formulation. A variable such as

$X(1,1)$ would be used to indicate the movement of material within a section. The system is designed to use half the section length as the the average haul distance for variables such as $X(1,1)$.

The cost elements associated with each variable, defined earlier as $E(C_i)$, become the cost coefficients in the objective function. Thus, the objective function can be written as:

Minimize:

$$Z = E(C_{1,3})X(1,3)+E(C_{1,4})X(1,4)+\ldots+E(C_{6,5})X(6,5) \qquad (27)$$

The constraints consist of the available quantity of cut at cut sections and the required quantity of fill at fill sections. Thus, the following constraints would apply:

$$\left.\begin{aligned} X(1,3) + X(1,4) + X(1,5) &= 10 \\ X(2,3) + X(2,4) + X(2,5) &= 8 \\ X(6,3) + X(6,4) + X(6,5) &= 2 \end{aligned}\right\} \text{ Cut Constraints } (28)$$

$$\left.\begin{aligned} X(1,3) + X(2,3) + X(6,3) &= 4 \\ X(1,4) + X(2,4) + X(6,4) &= 4 \\ X(1,5) + X(2,5) + X(6,5) &= 3. \end{aligned}\right\} \text{ Fill Constraints } (29)$$

The standard non-negative constraints:

$$X(i,j) \geq 0 \qquad (30)$$

complete the formulation of this simple problem consisting of 9 variables and 6 constraints.

Stark (1983) has extended this formulation to include: borrow/waste locations, swell and shrinkage factors, and setup costs.

The formulation described, while useful when the material types are uniform (i.e., all earth), does not address the key issue of determining the amount of rock included in the cut areas. A third index, k, will therefore be added to indicate the type of material. Futhermore, the uncertain quantities of rock and earth cause the cut stipulations (right-hand side of cut constraints) to be stochastic and not in conformance with the standard deterministic LP formulation. Therefore, a special approach to the LP formulation, allowing for stochastic cut stipulations, is required. Note that the use of the stochastic cost coefficients, C_i, does not interfere with the standard LP formulation (Aguilar:1973) if the expected values, $E(C_i)$, are used for the cost coefficients.

The problem posed by the uncertain quantities of earth and rock amount to uncertainties in the production quantities of the model. Dantzig (1955) proposed a method to handle uncertain demand in LP but it is not known if such a technique can be applied to uncertain production. Charnes and Cooper (1959) developed a technique, known as chance constrained programming, which allows, according to a specified probability, the constraints to be violated. This topic will be considered in the following section.

A comment should be made here about the possibility of extending the standard LP transportation problem to include transshipment. It is not considered feasible to do so for the following reasons. First of all, available space is usually at a premium during the earthmoving stage of highway construction and would preclude the creation of intermediate storage sites. Next, it is doubtful that the resultant cost of using transshipment would be less since loading and placement operations are costly. Finally, it is not felt that the level of accuracy possible in earthwork estimating warrants the more involved formulation required for considering transshipment.

Chance Constrained Programming

Charnes and Cooper (1959) developed a technique called chance constrained programming which is a type of statistical linear programming. It allows, with a small probability, violation of the constraints. Thus, it provides a means of combining optimization within probabilistic situations.

Under chance constrained programming, the general form of the constraints for a minimization problem is:

$$P\left[\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk} \geq b_{ik}\right] \geq \alpha_i \quad \begin{matrix} i=1,\ldots,m \\ j=1,\ldots,n \end{matrix} \qquad (31)$$

where P means probability

i = source station

j = destination station

k = type of material (Note: Only rock is considered in chance constraints so a summation over k is not needed.)

α_i = value of the probability satisfying the constraint, a normally distributed random variable with a mean of 0 and standard deviation of 1 [i.e., $\alpha_i \rightarrow N(0,1)$].

Figure 5-3 graphically shows the area of allowable risk, $1-\alpha$, defined by the chance constrained formulation. The risk is represented by the probability that the random variables b_{ik} will take on values such that the constraints are violated, that is:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ijk} X_{ijk} < b_{ik} \quad \begin{matrix} i=1,\ldots,m \\ j=1,\ldots,n \end{matrix} \tag{32}$$

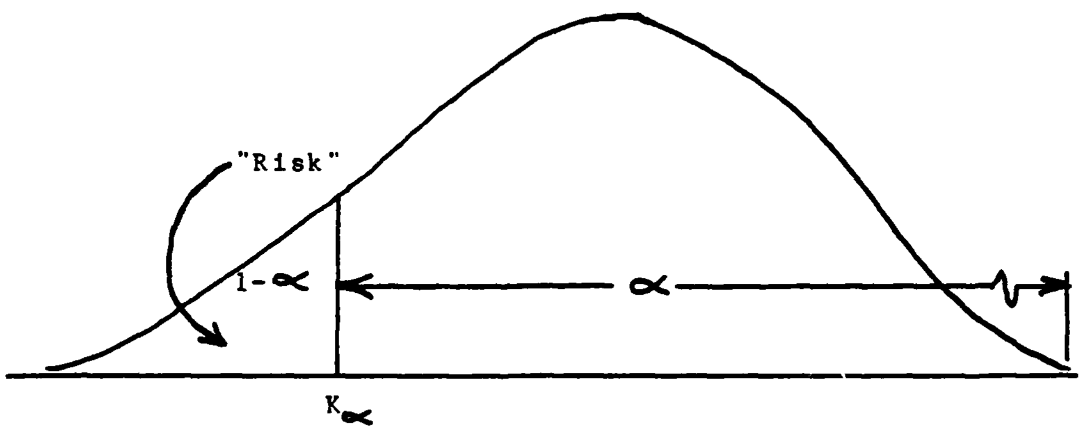

FIGURE 5-3 Area of Allowable Risk
(Sposito, 1975:135)

The objective of chance constrained programming is to "determine the optimal non-negative solution vector which will 'probably' satisfy each of the constraints when the random parameters take on their values" (Aguilar, 1973:337). In order to apply linear programming theory, the probabilistically-structured constraints must be converted into deterministic ones.

Assumptions

Aguilar (1973:337) summarizes the assumptions that are standard for chance constrained programming problems:

1. The structural coefficients, a_{ijk}, are constant parameters.
2. The stipulations, b_{ik} have known multivariate normal distributions.
3. The cost coefficients, C_{ijk}, have known distributions and are statistically independent of the stipulations, b_i.
4. The variables, X_{ijk}, must be determined before the values taken by any of the random parameters are known.

Model

In the proposed model for earthwork estimating, the general formulation is as follows.

Objective Function.

$$\text{MIN } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{o} E(C_{ijk}) X_{ijk} \tag{33}$$

Constraints.

$$\text{Subject to } X_{ijk} \geq 0 \quad \text{for } \begin{array}{l} i=1,\ldots,m \\ j=1,\ldots,n \\ k=1,\ldots,o \end{array} \tag{34}$$

$$\text{and } P\left\{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk} \geq b_i\right\} \geq \alpha_i \quad \text{for } \begin{array}{l} i=1,\ldots,m \\ j=1,\ldots,n \end{array} \tag{35}$$

Definitions.

Z = total cost of earthmoving

$E(C_{ijk})$ = unit cost coefficents

X_{ijk} = quantity of material type k moved from station i to station j

a_{ijk} = structural coefficients that account for swell and shrinkage

b_i = random valued stipulations representing the quantities of material (earth and rock) available at source stations

α_i = probability that the rock quantity constraints will be satisfied.

Conversion of Constraints

If $E(b_i)$ and σ_{b_i} are assumed to be the expected value and the standard deviation, respectively, of the random variable b_i then, according to the second assumption, the b_i's are normally distributed, i.e.,

$$b_i \dashrightarrow \text{Normal } (E(b_i), \sigma_{b_i}).$$

Then

$$Z = \frac{b_i - E(b_i)}{\sigma_{b_i}} \dashrightarrow \text{Normal } (0,1) \tag{36}$$

The probabilistic constraints given in equation (35) can now be converted to deterministic ones by the following relationship:

$$P\left\{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk} \geq b_i\right\} =$$

$$P\left\{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk}-E(b_i)}{\sigma\, b_i} \geq \frac{b_i-E(b_i)}{\sigma\, b_i}\right\} \geq \alpha_i \qquad (37)$$

for $i=1,\ldots,m$
$j=1,\ldots,n.$

Now, letting

$$K\alpha_i = \frac{a_{ijk}X_{ijk}-E(b_i)}{\sigma\, b_i} \qquad (38)$$

and using the relationship,

$$P\left\{K\ \alpha_i \geq \frac{b_i-E(b_i)}{\sigma\, b_i}\right\} = \alpha_i \qquad (39)$$

the following expression,

$$P\left\{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk}-E(b_i)}{\sigma\, b_i} \geq \frac{b_i-E(b_i)}{\sigma\, b_i}\right\} \geq \alpha_i \qquad (40)$$

is true if and only if,

$$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk}-E(b_i)}{\sigma\, b_i} \geq K\ \alpha_i \qquad (41)$$

when the last equation is rewritten as:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijk}X_{ijk} \geq E(b_i) + K\ \alpha_i\,\sigma\, b_i \qquad (42)$$

one has the probabilistic constraints converted to deterministic ones and the standard linear programming formulation can proceed.

Referring back to Figure 5-3, one can see the relationship between Z and $K\alpha_i$

$$P(Z \geq K\alpha_i) = \alpha_i \tag{43}$$

where $K\alpha_i$ = number of standard deviations to the left or right of zero mean

= probability that the random variable Z will lie to the right of $K\alpha_i$.

Hence, one only has to select either $K\alpha_i$ or α_i and the appropriate Z value can be obtained from tables that tabulate the area under the normal curve.

Summary

At this point, it is appropriate to reflect on the key elements presented in the last two chapters by recalling the objectives as described in Chapter One of this thesis. The first objective was to incorporate uncertainty into the estimation of rock quantities. Chance Constrained Programming (CCP) was the technique selected to accomplish this task. In essence, CCP converts probabilistically structured rock quantity constraints into deterministic ones that fit the standard LP format. The assumptions made in using CCP is that the estimates of rock quantity can be represented by a normal distribution with the estimator being able to input a mean and standard deviation for each section of rock cut.

The second objective was to integrate probability into the cost estimating process. The PERT-type, 3-value cost estimating method, as explained in Chapter Four, was adapted to fulfill this objective. The estimator is responsible for inputing cost data corresponding to three cost elements consisting of excavation cost, haul cost, and compaction cost. These cost elements, when combined and adjusted for swell/shrinkage, are the coefficients of the variables appearing in the objective function of the LP formulation.

The third objective was to determine the optimum cut/fill distribution of earthwork quantities. The LP formulation developed by Stark (1972) and extended to include CCP for rock quantities accomplishes this objective efficiently through the use of the simplex method.

The first three objectives, therefore, have been attained -- at least in the conceptual sense. The resulting proposed system, although containing already established techniques, is unique by virtue of both its structure and its application. The combination of probabilistic cost estimates and LP methods is innovative as is the application of PERT-type estimates to project cost rather than project duration.

The next chapter presents a description of the entire proposed system and illustrates how the last objective, creation of a total unit cost distribution, is achieved.

As such, it integrates the models presented in the last two chapters and illustrates, by way of an example problem, the interaction and interdependencies that exist.

CHAPTER SIX

PROPOSED EARTHWORK ESTIMATING SYSTEM

The previous chapters have provided the background and the theoretical models that are incorporated into the proposed system that is presented in Figure 6-1. The purposes of this chapter are to: (1) discuss the assumptions made with regard to the design of the proposed system, (2) provide a complete description of the system which integrates the previously described models, (3) illustrate the application of the developed system by solving an example problem, and (4) discuss why the system was programmed in the APL language to provide a user-oriented, interactive system.

Assumptions

The following assumptions were made during the design of the proposed system:

1. The system user has the necessary information (i.e., borings, field drilling data) and ability to estimate (by the mean and standard deviation) the quantities of rock in each cut section.
2. The system user has the responsibility for determining fleet configurations (i.e., fleet type and composition).
3. The system user has the necessary information and ability to account for variable production

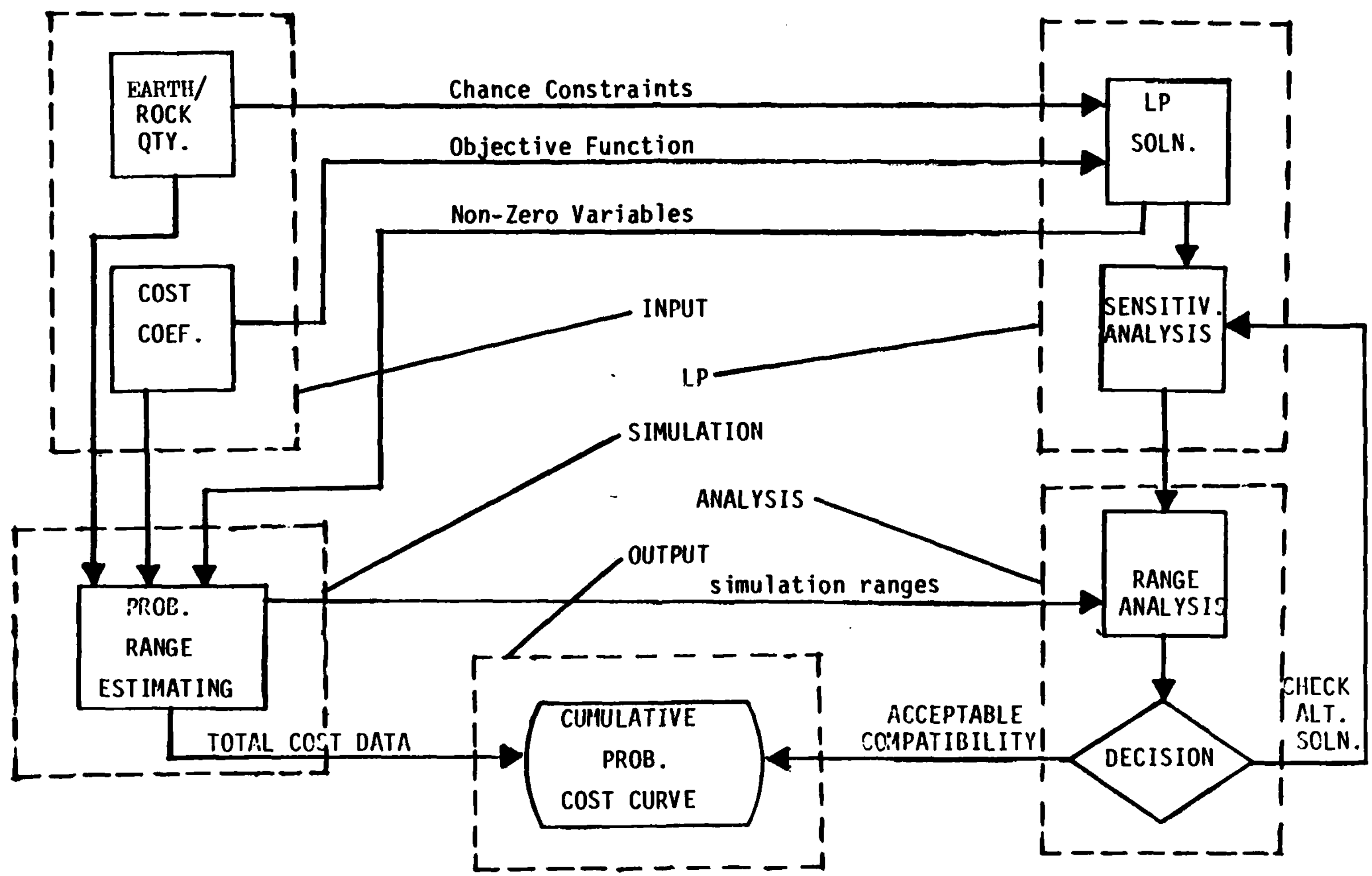

FIGURE 6-1 Proposed System for Earthwork Estimating

rates by formulating three-value cost estimates for each phase (i.e., excavation, hauling, and compaction) of the earthmoving operation.

4. Soil information is available to enable the system user to estimate the swell/shrinkage factors of earth and rock.

5. The system user is familar with basic LP problem formulation.

Integration of Models

Recall that Chapter Four presented the beta, normal, and double-triangular models. Chapter Five described the linear programming (LP) formulation and chance constrained programming which adopted a normal distribution for the estimated rock quantities. This section will begin by explaining the input phase of the proposed system, next discuss the LP formulation and, finally, the simulation phase which generates the desired output.

Input Phase

This phase involves the input of soil and cost data and the calculation of cost coefficients that are subsequently used in the LP formulation. The system user can input either a single value or three values (corresponding to a deterministic or probabilistic estimate, respectively) for the swell factor, excavation cost, haul cost, and compaction cost. The approximate beta (or PERT-type) model, discussed in Chapter Four, is used to calculate the mean of the swell/shrinkage factors and the mean of the cost coefficients. Recall from Chapter Four that the cost coefficient consists of the excavation cost plus the haul cost times a haul distance plus the compaction costs. The swell/shrinkage factor is applied to both the haul and compaction cost elements. The resultant sum of these three cost elements is the cost coefficient for a particular variable. Note that the variance of the cost coefficients does not have to be calculated because the cost coefficients will be replicated a number of times (at least thirty) during the simulation phase. The resulting distribution of a particular cost coefficient will be (according to the central limit theorem) normally distributed and, hence, the variance and standard deviation can be obtained using standard sampling statistics.

The input phase, then, uses the approximate beta distribution to obtain a mean value for the swell/shrinkage factor and for each cost coefficient. The cost coefficients are used in the objective function of the LP formulation. The next section will discuss the model interaction in the LP formulation.

LP Formulation

The LP problem is formulated as an "enumeration-type" transportation problem (i.e., every possible movement of material from a cut or borrow to a fill or waste is represented by a term, such as $E(C_{i,j,k})$ X (1,3,E), indicating the movement of earth from section 1 to section

3). The $E(C_{i,j,k})$ coefficients are produced by the input phase of the proposed system. These terms appear in the objective function of the LP formulation, as described in Chapter Five. Any standard LP solution package can be used to solve the formulated problem.

The chance-constrained model becomes evident during the formulation of the cut constraints. For a particular cut, there can be one of three possibilities: (1) all earth, (2) all rock or, (3) some combination of earth and rock. The chance-constrained model addresses the third possibility listed above. The act of determining (and estimating) the earth/rock composition in a cut is, perhaps, one of the most common and most troublesome problems confronting the earthwork contractor. As explained in Chapter Five, the approach taken is to replace the random variable (rock quantity in a cut section) by a deterministic equivalent (assuming the rock quantity estimate is normally distributed). The standard simplex method is then used to solve the LP problem. The system user is responsible for correctly formulating the problem with regard to the cut and fill constraints. A sketch of the highway profile, with the 1000-foot sections and cut or fill volumes shown, is helpful in this regard.

Simulation Phase

Once the LP solution is obtained, the non-zero variables are identified. The coefficients of these variables will then be replicated a number of times (subject to user control) using the double-triangular distribution discussed in Chapter Four. The user must input the variable coefficients that are to be replicated as well as the number of replications. The system can then provide the following information: (1) the minimum and maximum value for each coefficient entered, (2) the statistics (mean, standard deviation, max, min, and range) of the total unit cost, (3) the percentiles of the total unit cost, and (4) a plot of the cumulative probability versus the total unit cost. The information included in (1) and (2) above are routinely provided while the information in (3) and (4) above is subject to the needs of the user. For example, the user can request an 85% reading (3) (meaning the total unit cost value that corresponds to an 85% probability of not being exceeded) and then a plot of the cumulative probability versus the total unit cost (4) or either of these options.

Example Problem

This section illustrates the use of the proposed system by presenting the details of how a simplified problem is solved. The example problem is one which has been solved by Stark (1983), but it is modified to include both earth and rock rather than just one material. The solution can be explained in the following steps: (1) description, (2) quantity take-off, (3) calculation of cost coefficients, (4) LP formulation, (5) simulation of LP output coefficients, and, (6) interpretation of output and, (7) comparison of cost estimates.

Description

The problem consists of determining the earthwork distribution for a 6000-foot section of highway. Figure 6-2 shows a plan and profile of the highway with the 1000-foot sections. Note that the profile can be partitioned into sections of any length desired, but 1000-foot sections are most common. A waste and borrow area is shown on the plan view of Figure 6-2. The user should also realize that as the length of sections is halved, the number of variables in the LP formulation is multiplied by four if two types of material (earth and rock) are considered.

It is not necessary to draw a haul-mass diagram (as shown in Figures 3-2 and 5-1) unless the user wants a visual depiction of the relative cut/fill distribution. It will be necessary, however, to draw a haul-mass or an arrow allocation diagram (as shown in Table 3-2) if the user wants to compute the average haul distance. Recall that the average haul distance is an important parameter in determining fleet selection/composition.

Quantity Take-off

Table 6-1 summarizes the quantities of cut/fill. Note that sections 3 and 6 contain both cut and fill quantities. Although the total cut and fill quantities appear to be equal, application of the swell/shrinkage factors could result in either a net cut or fill quantity.

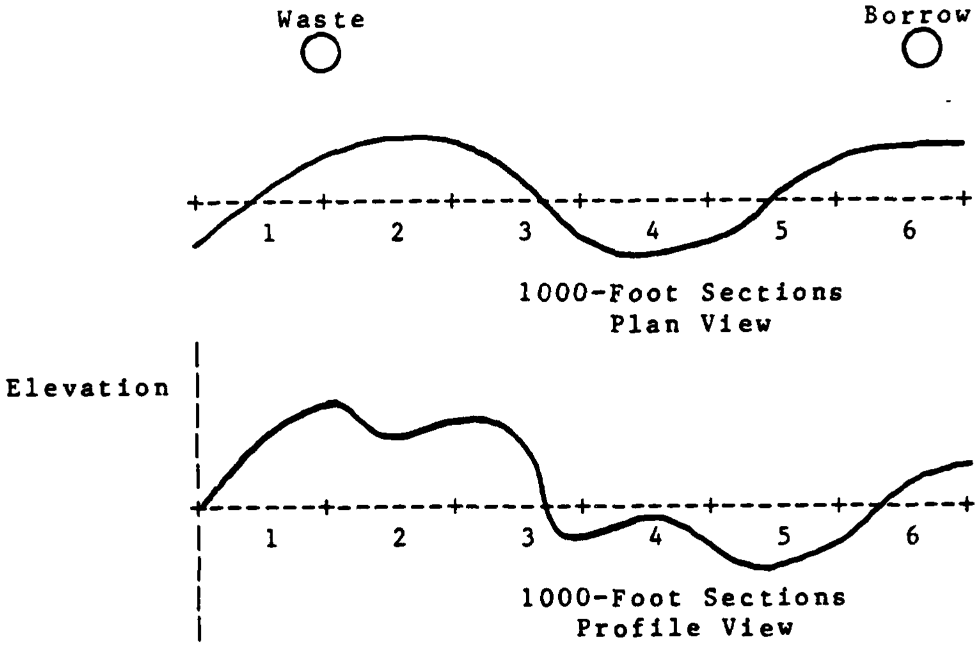

FIGURE 6-2 Plan and Profile of Example Problem

A typical set of plans for a PennDOT Highway Project provides the total cut/fill quantities per 1000-foot section, but does not show the quantity of rock. As mentioned earlier in the assumptions section, the user is responsible for estimating the mean and standard deviation for the rock quantity in each section.

Calculation of Cost Coefficients

Table 6-2 shows the estimated costs that are input by the user. Note that three-valued estimates are given, but the system user could also have only input a single value for each cost element (i.e., excavation of earth -- $400, compaction of rock -- $1200 etc.) if a deterministic estimate were desired.

TABLE 6-1

Quantity Summary for Example Problem

Quantities of Cut/Fill (1000 BCY)								
Section Number		1	2	3	4	5	6	Totals
Cut	Earth	40	70	45			35	190
	Rock (Mean/Std. Dev.)	10/2	20/3	5/1			15/3	50/8
Fill				30	40	90	80	240

The cost coefficients are calculated using the equation

$$C_T = C_e + (C_h \times d + C_c)\ SF \qquad (44)$$

where SF is the swell factor and the other terms are as defined in Chapter Four and shown in Table 6-2. The following swell/shrinkage factors are assumed for this problem:

	Swell Factor	Shrinkage Factor
Earth	1.2	0.9
Rock	1.5	1.3

The swell factors, in addition to being used to calculate the cost coefficients, are also applied to the waste area capacity constraints, as applicable. The

TABLE 6-2

Cost Data for Example Problem

Excavation (including loading), C_e		\$ per 1000 BCY (3-value estimate) Low	Mode	High
Along Roadway:	Earth	350,	375,	450
	Rock	1200,	1800,	2000
From Borrow Pit		200,	225,	275

Compaction (including unloading), C_c		\$ per 1000 LCY (3-value estimate) Low	Mode	High
Along Roadway:	Earth	850,	900,	925
	Rock	1150,	1225,	1250
At Landfill:	Earth	315,	350,	370
	Rock	425,	450,	500

Haul, C_h	\$ per 1000-foot haul, d (3-value estimate) Low	Mode	High
Earth	275,	300,	350
Rock	310,	350,	370

shrinkage factors are applied to the fill constraints, as shown in the next section.

A typical calculation of the cost coefficients can be illustrated by computing the coefficient for X(1,3,E). Recall that X(1,3,E) represents the quantity of earth that is to be moved from section 1 (cut) to section 3 (fill). The cost estimates are taken from Table 6-2 and the PERT-type mean values are calculated as follows using equation (44):

$$C_T = C_e + (C_h \times d + C_c)\ SF$$

$$= \frac{350+(4)375+450}{6} + \left[\frac{275+(4)300+350}{6}(2) + \frac{850+(4)900+925}{6} \right] 1.2$$

$$= 383 + [(304)2 + 896]\ 1.2$$

$$= \$2188 \text{ per } 1000 \text{ BCY}$$

The other coefficients are calculated in a similar manner and are shown in the objective function of the LP formulation.

LP Formulation

The notation used to define the variables consists of two numbers and a letter. The first number is the source or origin section of the roadway and the second number is the destination section. The letter (E for earth and R for rock) describes either the type of material or an off-roadway source (B for borrow) or destination (W for waste).

The number of variables in the LP formulation can be approximated by the following formula:

$$NVAR = NM \times NCS \times NFS \tag{45}$$

where NVAR = number of variables in the LP formulation

NM = number of materials considered (i.e., earth, rippable rock, solid rock, etc.)

NCS = number of cut sections including borrow areas (as determined from the profile and section length)

NFS = number of fill sections including waste areas (as determined from the profile and section length).

Note that, while it is theoretically possible to consider more than two types of material for NM (earth and rock), this example and the case study, which appears in the following chapter, limits NM to two.

Using equation (45), one calculates the number of variables in the example problem as:

$$\begin{aligned} NVAR &= NM \times NCS \times NFS \\ &= 2 \times 5 \times 5 \\ &= 50. \end{aligned}$$

However, the following combinations must be deleted:

borrow to fill only includes earth

-4 variables

borrow to sections 1 and 2 is not realistic

-2 variables.

The resulting objective function, therefore, contains 44 variables. This example illustrates how the inclusion of existing borrow (B) and waste (W) sites is handled in the LP formulation. Note that the LP formulation can also be used to select sites for borrow and waste. This technique will be demonstrated in the case study analysis in the next chapter.

Objective Function.

Minimize:

$$
\begin{aligned}
Z = {} & 2188\ X(1,3,E) + 4598\ X(1,3,R) + 2553\ X(1,4,E) + \\
& 5118\ X(1,4,R) + 2918\ X(1,5,E) + 5638\ X(1,5,R) + \\
& 3283\ X(1,6,E) + 6158\ X(1,6,R) + 1165\ X(1,W,E) + \\
& 2935\ X(1,W,R) + 1823\ X(2,3,E) + 4078\ X(2,3,R) + \\
& 2188\ X(2,4,E) + 4598\ X(2,4,R) + 2553\ X(2,5,E) + \\
& 5118\ X(2,5,R) + 2918\ X(2,6,E) + 5638\ X(2,6,R) + \\
& 1165\ X(2,W,E) + 2935\ X(2,W,R) + 1641\ X(3,3,E) + \\
& 3818\ X(3,3,R) + 1823\ X(3,4,E) + 4078\ X(3,4,R) + \\
& 2188\ X(3,5,E) + 4598\ X(3,5,R) + 2553\ X(3,6,E) + \\
& 5118\ X(3,6,R) + 1530\ X(3,W,E) + 3455\ X(3,W,R) + \\
& 2553\ X(6,3,E) + 5118\ X(6,3,R) + 2188\ X(6,4,E) + \\
& 4598\ X(6,4,R) + 1823\ X(6,5,E) + 4078\ X(6,5,R) + \\
& 1641\ X(6,6,E) + 3818\ X(6,6,R) + 2625\ X(6,W,E) + \\
& 5015\ X(6,W,R) + 2764\ X(B,3,E) + 2399\ X(B,4,E) + \\
& 2034\ X(B,5,E) + 1669\ X(B,6,E) \qquad (46)
\end{aligned}
$$

Cut Constraints.

$$
\begin{aligned}
& X(1,3,E) + X(1,3,R) + X(1,4,E) + X(1,4,R) + \\
& X(1,5,E) + X(1,5,R) + X(1,6,E) + X(1,6,R) + \\
& X(1,W,E) + X(1,W,R) = 50 \qquad (47)
\end{aligned}
$$

$$X(2,3,E) + X(2,3,R) + X(2,4,E) + X(2,4,R) +$$
$$X(2,5,E) + X(2,5,R) + X(2,6,E) + X(2,6,R) +$$
$$X(2,W,E) + X(2,W,R) = 90 \qquad (48)$$

$$X(3,3,E) + X(3,3,R) + X(3,4,E) + X(3,4,R) +$$
$$X(3,5,E) + X(3,5,R) + X(3,6,E) + X(3,6,R) +$$
$$X(3,W,E) + X(3,W,R) = 50 \qquad (49)$$

$$X(6,3,E) + X(6,3,R) + X(6,4,E) + X(6,4,R) +$$
$$X(6,5,E) + X(6,5,R) + X(6,6,E) + X(6,6,R) +$$
$$X(6,W,E) + X(6,W,R) = 50 \qquad (50)$$

The chance-constrained rock quantity constraints are formulated with a 5 percent chance of the constraints being violated. Therefore, using a table of the areas under a normal curve, we have

$$P(Z \geq +1.65) = 0.95 \qquad (51)$$

where the +1.65 is the Z value from the normal curve table. The Z value of +1.65 corresponds to the area under the normal curve from +1.65 standard deviations to $+\infty$ or 5 percent.

The rock quantity variables are normalized using the relationship,

$$Z = \frac{b_i - E(b_i)}{\sigma_{b_i}}. \qquad (52)$$

For cut section 1 we have,

$$\frac{X(1,3,R)+X(1,4,R)+X(1,5,R)+X(1,6,R)+X(1,W,R)-10}{2} \geq +1.65, \tag{53}$$

where $E(b_i) = 10$ and $\sigma_{b_i} = 2$ from Table 6-1.

The above equation reduces to the final deterministic form as

$$X(1,3,R) + X(1,4,R) + X(1,5,R) + X(1,6,R) + X(1,W,R) \geq 13.3 \tag{54}$$

The chance-constrained rock constraints for cut sections 2, 3, and 6 are calculated in the same manner and result in the following:

$$X(2,3,R) + X(2,4,R) + X(2,5,R) + X(2,6,R) + X(2,W,R) \geq 24.95 \tag{55}$$

$$X(3,3,R) + X(3,4,R) + X(3,5,R) + X(3,6,R) + X(3,W,R) \geq 6.65 \tag{56}$$

$$X(6,3,R) + X(6,4,R) + X(6,5,R) + X(6,6,R) + X(6,W,R) \geq 19.95 \tag{57}$$

<u>Fill Constraints</u>. These constraints include the shrinkage factors listed earlier.

$$.9\ X(1,4,E) + 1.3\ X(1,4,R) + .9\ X(2,4,E) + 1.3\ X(2,4,R) + .9\ X(3,4,E) + 1.3\ X(3,4,R) + .9\ X(6,4,E) + 1.3\ X(6,4,R) + .9\ X(B,4,E) = 40 \tag{58}$$

$$.9\ X(1,5,E) + 1.3\ X(1,5,R) + .9\ X(2,5,E) + 1.3\ X(2,5,R) + .9\ X(3,5,E) + 1.3\ X(3,5,R) + .9\ X(6,5,E) + 1.3\ X(6,5,R) + .9\ X(B,5,E) = 90 \tag{59}$$

$$.9\ X(1,6,E) + 1.3\ X(1,6,R) + .9\ X(2,6,E) + 1.3\ X(2,6,R) + .9\ X(3,6,E) + 1.3\ X(3,6,R) + .9\ X(6,6,E) + 1.3\ X(6,6,R) + .9\ X(B,6,E) = 80 \quad (60)$$

$$.9\ X(1,3,E) + 1.3\ X(1,3,R) + .9\ X(2,3,E) + 1.3\ X(2,3,R) + .9\ X(3,3,E) + 1.3\ X(3,3,R) + .9\ X(6,3,E) + 1.3\ X(6,3,R) + .9\ X(B,3,E) = 30 \quad (61)$$

If the borrow and/or waste areas have capacity limitations, these are included as additional constraints. In this example, the borrow site is assumed to have a 50,000 BCY and the waste site is assumed to have a 75,000 BCY capacity. The constraints for the borrow and waste areas are as follows.

Borrow.

$$X(B,3,E) + X(B,4,E) + X(B,5,E) + X(B,6,E) \leq 50 \quad (62)$$

Waste.

$$1.2\ X(1,W,E) + 1.5\ X(1,W,R) + 1.2\ X(2,W,E) + 1.5\ X(2,W,R) + 1.2\ X(3,W,E) + 1.5\ X(3,W,R) + 1.2\ X(6,W,E) + 1.5\ X(6,W,R) \leq 75 \quad (63)$$

Note that the swell factors are applied to the waste area constraint since this material is normally not compacted and its loose state (LCY) occupies more volume than its natural state (BCY).

The non-negativity constraints (i.e., $X(i,j,k) \geq 0$) complete the LP formulation of this example problem which contains 44 variables and 14 constraints.

Simulation of LP Output Coefficients

The LP solution routinely provides a solution in a form like that shown in Table 6-3. As an example, the first line in Table 6-3 means that 12.97 thousand BCY of earth is to be moved from section 1 to the waste site. The reduced cost of 0.00 indicates that X1WE is a basic variable. Since we are not concerned with variables having a value of zero, only the non-zero valued variables, as identified by the LP solution, will be simulated to determine a unit cost distribution. The user inputs the number of replications desired, the confidence factor, the variable parameters (i.e., source, destination, and material type), and the quantity of material for each variable as determined from the LP solution. Recall that the confidence factor, P (refer back to Figure 4-5), is a parameter of the double-triangular distribution. It represents the probability that the most likely cost value of a cost element will not be exceeded. The proposed system uses Monte-Carlo sampling to replicate each cost element and obtain a unit cost distribution. Table 6-4 shows the 30 unit cost values after the example problem was simulated for 30 replications. The unit cost ranged from \$2.33 to \$2.62 per BCY and the statistics are shown below the unit cost values.

TABLE 6-3

LP Output for Example Problem

LP Optimum Found at Step 12

Objective Function Value

$677614.75

Variable	Value	Reduced Cost
X1WE	12.97	0.00
X1WR	13.30	0.00
X23E	20.61	0.00
X24E	44.44	0.00
X25R	24.95	0.00
X15E	11.00	0.00
X35E	43.35	0.00
X35R	6.65	0.00
X66E	30.05	0.00
X66R	19.95	0.00
XB6E	30.02	0.00
X13E	12.73	0.00

TABLE 6-4

Simulated Unit Costs for Example Problem

(30 Replications)

($/BCY)

2.33	2.35	2.36	2.38	2.40
2.40	2.41	2.43	2.44	2.45
2.46	2.47	2.47	2.48	2.48
2.49	2.49	2.50	2.51	2.51
2.52	2.52	2.53	2.54	2.55
2.55	2.56	2.57	2.59	2.62

Maximum	2.62
Minimum	2.33
Average	2.48
Std. Dev.	0.074
Range	0.29
No. Obs.	30

Interpretation of Output

The proposed estimating system takes advantage of two types of output analysis. First, there is the sensitivity analysis normally available when the LP package is evaluated. Table 6-5 is a copy of the computer-generated sensitivity analysis.

The 12 variables appearing in Table 6-3 are the solution or basic variables and are identified by a "B" to the left of the variables in Table 6-5. The remaining 32 variables in Table 6-5 are non-basic. The two columns under "OBJ COEFFICIENT RANGES" are used for sensitivity analysis of both basic and non-basic variables. As an example, consider the basic variable X15E. According to the third and fourth columns in Table 6-5, this variable does not have any allowable increase or decrease. Thus, if the coefficient 2918 were either increased or decreased by any amount, the variable X15E would no longer be basic and cease to be a solution variable. As an example of sensitivity analysis for non-basic variables, consider X13R. It has an allowable increase of infinity and an allowable decrease of 185.33. This means that if the coefficient 4598 is changed within this range, X13R will continue to be a non-basic variable. However, if the coefficient is decreased by more that 185.33, the variable will become basic and enter the LP solution.

The continuation of Table 6-5 provides the information needed to analyze the sensitivity of the righthand side

TABLE 6-5

Sensitivity Analysis
for
Example Problem

OBJ COEFFICIENT RANGES

	VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
	X13R	4598.000000	INFINITY	185.334473
	X14E	2553.000000	INFINITY	0.000488
	X14R	5118.000000	INFINITY	178.112793
B	X15E	2918.000000	0.000000	0.000244
	X15R	5638.000000	INFINITY	170.890625
	X16E	3283.000000	INFINITY	449.000244
	X16R	6158.000000	INFINITY	812.223877
B	X1WE	1165.000000	241.693924	95.997620
B	X1WR	2935.000000	170.890625	1770.000000
B	X23E	1823.000000	0.000000	0.000244
	X23R	4078.000000	INFINITY	14.447510
B	X24E	2188.000000	0.000244	INFINITY
	X24R	4598.000000	INFINITY	7.225830
	X25E	2553.000000	INFINITY	0.000000
B	X25R	5118.000000	7.225830	1785.886720
	X26E	2918.000000	INFINITY	449.000000
	X26R	5638.000000	INFINITY	641.333252
	X2WE	1165.000000	INFINITY	364.999756
	X2WR	2935.000000	INFINITY	349.113037
	X33E	1641.000000	INFINITY	183.000000
	X33R	3818.000000	INFINITY	274.447510
	X34E	1823.000000	INFINITY	0.000244
	X34R	4078.000000	INFINITY	7.225830
B	X35E	2188.000000	0.000244	INFINITY
B	X35R	4598.000000	7.225830	1630.886720
	X36E	2553.000000	INFINITY	449.000000
	X36R	5118.000000	INFINITY	641.333252
	X3WE	1530.000000	INFINITY	1094.999760
	X3WR	3455.000000	INFINITY	1389.113040
	X63E	2553.000000	INFINITY	1558.000000
	X63R	5118.000000	INFINITY	2233.106930
	X64E	2188.000000	INFINITY	828.000244
	X64R	4598.000000	INFINITY	1185.885250
	X65E	1823.000000	INFINITY	98.000000
	X65R	4078.000000	INFINITY	138.663086
B	X66E	1641.000000	98.000000	INFINITY
B	X66R	3818.000000	138.663086	1435.223630
	X6WE	2625.000000	INFINITY	2652.999760
	X6WR	5015.000000	INFINITY	3607.772460
	XB3E	2764.000000	INFINITY	1741.000240
	XB4E	2399.000000	INFINITY	1011.000490
	XB5E	2034.000000	INFINITY	281.000244
B	XB6E	1669.000000	444.000244	95.997620
B	X13E	2188.000000	0.000244	0.000000

TABLE 6-5 (Continued)

Sensitivity Analysis
for
Example Problem

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	90.000000	12.727761	12.966628
3	50.000000	11.005610	12.966628
4	50.000000	30.022247	19.977737
5	13.299999	12.966628	13.299999
6	24.949982	7.619277	12.727761
7	6.649999	24.762665	6.649999
8	19.949982	30.050018	19.949982
9	40.000000	11.669970	11.454989
10	80.000000	17.979965	27.020020
11	75.000000	INFINITY	39.490036
12	90.000000	11.669970	9.905053
13	50.000000	32.908356	12.966628
14	50.000000	INFINITY	19.977737
15	30.000000	11.669970	11.454989

ranges which correspond to material quantity constraints. For example, the value of 90 for row 2 corresponds to equation (48) which is the cut constraint for section 2 indicating a total cut of 90 thousand BCY. The allowable increase and decrease of 12.73 and 12.97, respectively, means that as long as the actual quantity of cut in section 2 is within the range 77.03-102.73 (90-12.97 to 90+12.73) the solution variables will remain basic. Any increase or decrease beyond this range will result in a different solution and the current solution will no longer be optimum.

The second type of analysis is that available from the user options portion of the proposed system. The initial step compares the coefficient ranges produced by the simulation to those produced in the LP sensitivity analysis (Table 6-5). Table 6-6 presents the results of both the LP and simulated coefficient ranges for the example problem. The problem was simulated for thirty replications with a confidence factor of 67 percent.

The next step involves an evaluation of the coefficient ranges obtained from the LP and simulation phases. If the simulation range is bracketed by the LP range for each of the solution coefficients, the user is assured of an optimal cut/fill distribution and, provided the number of replications was adequate, can proceed with further graphical display options for the total unit cost.

If the LP and simulation ranges are incompatible, however, the user must answer at least two questions. First

TABLE 6-6

Comparison of Coefficient Ranges for Example Problem

Variable	Coefficient Ranges: Simulation / LP Sensitivity
X(1,W,E)	1100 - 1228 / 1069 - 1407
X(1,W,R)	2538 - 3133 / 1165 - 3106
X(2,3,E)	1749 - 1878 / 1823 - 1823
X(2,4,E)	2098 - 2298 / 0000 - 2188
X(2,5,R)	4582 - 5266 / 3332 - 5125
X(1,5,E)	2752 - 3066 / 2918 - 2918

TABLE 6-6 (Continued)

Comparison of Coefficient Ranges for Example Problem

Variable	Coefficient Ranges: Simulation / LP Sensitivity
X(3,5,E)	2103 - 2262 / 0000 - 2188
X(3,5,R)	4070 - 4835 / 2967 - 4605
X(6,6,E)	1568 - 1722 / 0000 - 1739
X(6,6,R)	3242 - 4049 / 2383 - 3957
X(B,6,E)	1576 - 1751 / 1573 - 2113
X(1,3,E)	2096 - 2262 / 2188 - 2188

of all, is the incompatibility widespread among the solution coefficients? Next, was the number of replications chosen for the simulation adequate? If the answers to the above questions were no/yes, respectively, the user can most likely proceed without further action. If the answers were not no/yes, respectively, the user should repeat the simulation phase with at least thirty replications. This will serve to give a more representative range for the solution coefficients, which according to the central limit theorem will approximate a normal distribution. Next, the LP and simulation ranges should again be compared for compatibility. Hopefully, the ranges will be compatible at this point. If they are not, the user is left with two options: (1) assume the simulated ranges are correct and proceed (knowing that the LP solution will not be optimum for all values of the random coefficients) or, (2) re-evaluate the problem formulation (insuring that all variables, coefficients, and constraints were entered correctly) and then check the LP sensitivity analysis for possible alternative solutions. These can be identified by the presence of variables that have both a value and a reduced cost of zero in the LP solution. Any alternative LP solution would again have to be replicated by the simulation portion of the proposed system and then re-evaluated, as explained above.

For the example problem, Table 6-6 indicates that 9 of the 12 simulated coefficient ranges fall outside their respective LP ranges (only the variables X(1,W,E), X(6,6,E) and X(B,6,E) have totally compatible ranges). While it might be obvious to conclude that widespread incompatibility exists, such a conclusion would be premature. A closer look at the ranges in Table 6-6 shows that the majority of the incompatibility involves the upper values or tails of the simulated coefficients. Thus, the vast majority of the ranges are compatible if one neglects the upper tail of the simulated ranges. Keep in mind that the value selected for the confidence factor, P, will influence the simulated range.

An evaluation of the complete LP solution (not shown) for the example problem reveals that variables X(1,4,E), X(2,5,E), and X(3,4,E) have reduced costs of zero and, therefore, take on non-zero values in alternative solutions that result in the same objective function value. For example, Table 6-7 presents an alternative solution that includes variables X(1,4,E) and X(2,5,E) in place of X(1,3,E) and X(1,5,E). The system user can decide if alternative solutions provide significant advantages. For the example above, the alternative eliminates the 4000-foot haul required for variable X(1,5,E) and limits the maximum haul to 3000 feet. Depending on the fleets and configurations, uniform haul distances may be preferred. While it is a simple matter to determine the alternative solutions rapidly on the computer, the user must carefully evaluate them based on past experience, anticipated

TABLE 6-7

Alternative Solution for Example Problem

Objective Function Value

$677614.75

	Variable	Value	Reduced Cost
*	X14E	23.73	0.00
	X1WE	12.97	0.00
	X1WR	13.30	0.00
	X23E	33.33	0.00
	X24E	20.71	0.00
*	X25E	11.01	0.00
	X25R	24.95	0.00
	X35E	43.35	0.00
	X35R	6.65	0.00
	X66E	30.05	0.00
	X66R	19.95	0.00
	XB6E	30.02	0.00

* New variables in place of X13E and X15E

equipment availability, and haul road accessability in order to determine his optimum solution.

Based upon the experience of testing several problems with the proposed system, it appears that the first option above would be sufficient for most users. The primary reason for this opinion relates to the "law of diminishing return." While it may be possible to obtain completely compatible LP and simulation ranges, one must consider the expense in terms of time, computer cost, and expected benefit. It is felt that although precision in earthwork estimation is warranted and, in fact, a primary aim of this thesis, one must dismiss minor irregularities when faced with the fact that several other uncertainties still exist and most probably cannot be accounted for in any estimating system.

Comparison of Cost Estimates

The proposed system allows the user to obtain a plot of the cumulative probability versus total unit cost, as shown in Figure 6-3, and percentiles of the total unit cost, as shown in Table 6-8. The percentiles option is particularly useful because the user can specify any percentile desired and the system will calculate the equivalent total unit cost. Referring to Table 6-8, one sees the 10th to the 90th percentiles, as well as the lower and upper quartiles. These values are routinely supplied. Below these values, the user can enter any other percentiles desired. For this problem, the total unit costs corresponding to the 68th,

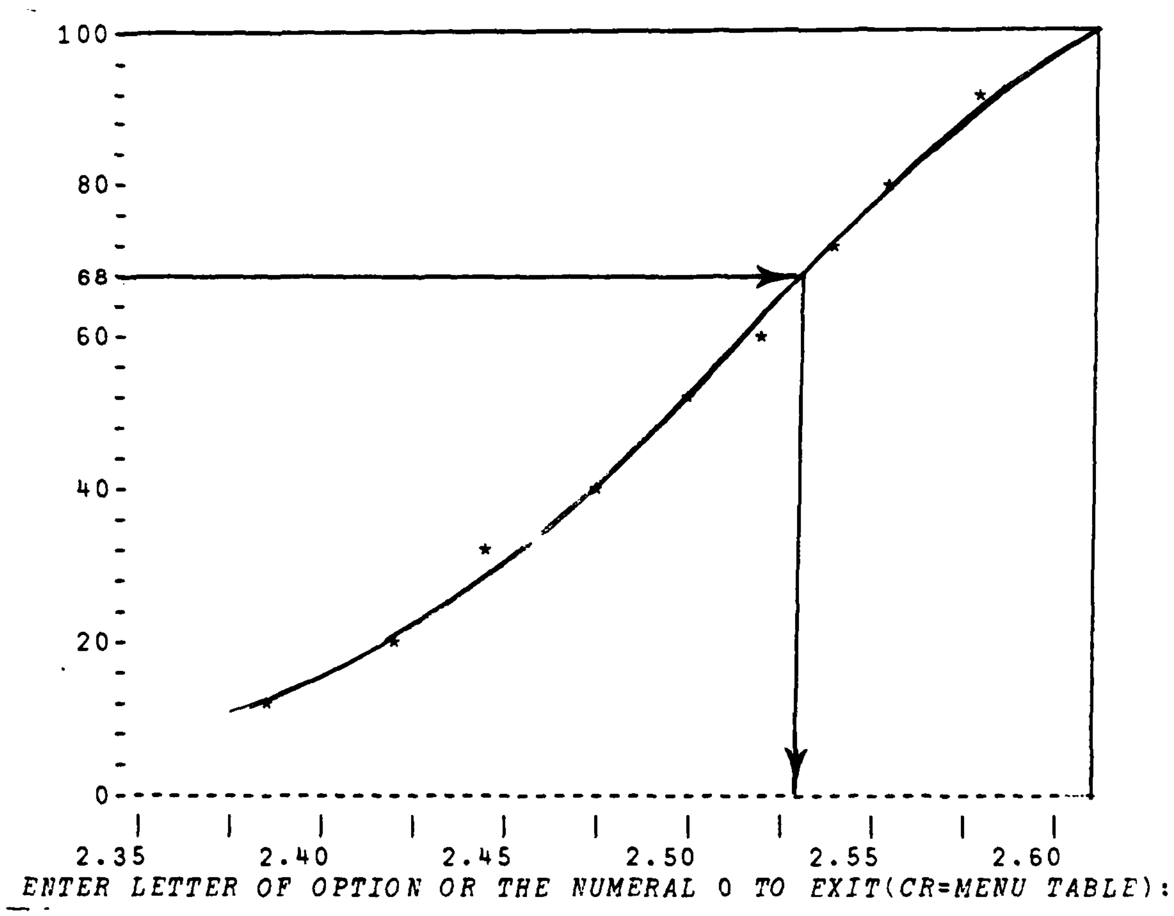

FIGURE 6-3 Distribution of Total Unit Cost

TABLE 6-8

Percentiles of Total Unit Cost
for Example Problem

Percent	Unit Cost	No. of Obs.
10.00	2.36	3
20.00	2.40	6
30.00	2.44	9
40.00	2.47	12
50.00	2.48	15
60.00	2.50	18
70.00	2.52	21
80.00	2.54	24
90.00	2.56	27

The lower quartile is: 2.42

The upper quartile is: 2.53

68.00	2.51	20
95.00	2.57	28
99.00	2.59	29

95th, and 99th percentiles were requested. The total unit cost corresponding to 68 percent confidence (i.e., 68 percent of the time this value would not be exceeded based on the estimated input) is $2.51 per BCY. Depending upon management policy, the user can readily obtain an estimated total unit cost that reflects any degree of risk desired. The plot in Figure 6-3 visually displays this same relationship between risk and cost and represents a major objective of the proposed system.

One might now ask how the estimate from the proposed system differs from that obtained using traditional estimating methods. Figure 6-4 shows the example problem profiles with arrows representing the movement of material between sections. The top figure represents the distribution obtained from the LP solution. The bottom figure represents a typical distribution scheme that was obtained using the arrow allocation diagram approach as discussed in Chapter Three. Table 6-9 is a summary of the cost estimate preparation using the arrow allocation diagram. Table 6-10 is the haul-mass data for the example problem.

The following comparison vividly reflects the differences between the proposed system estimate and a traditional estimate.

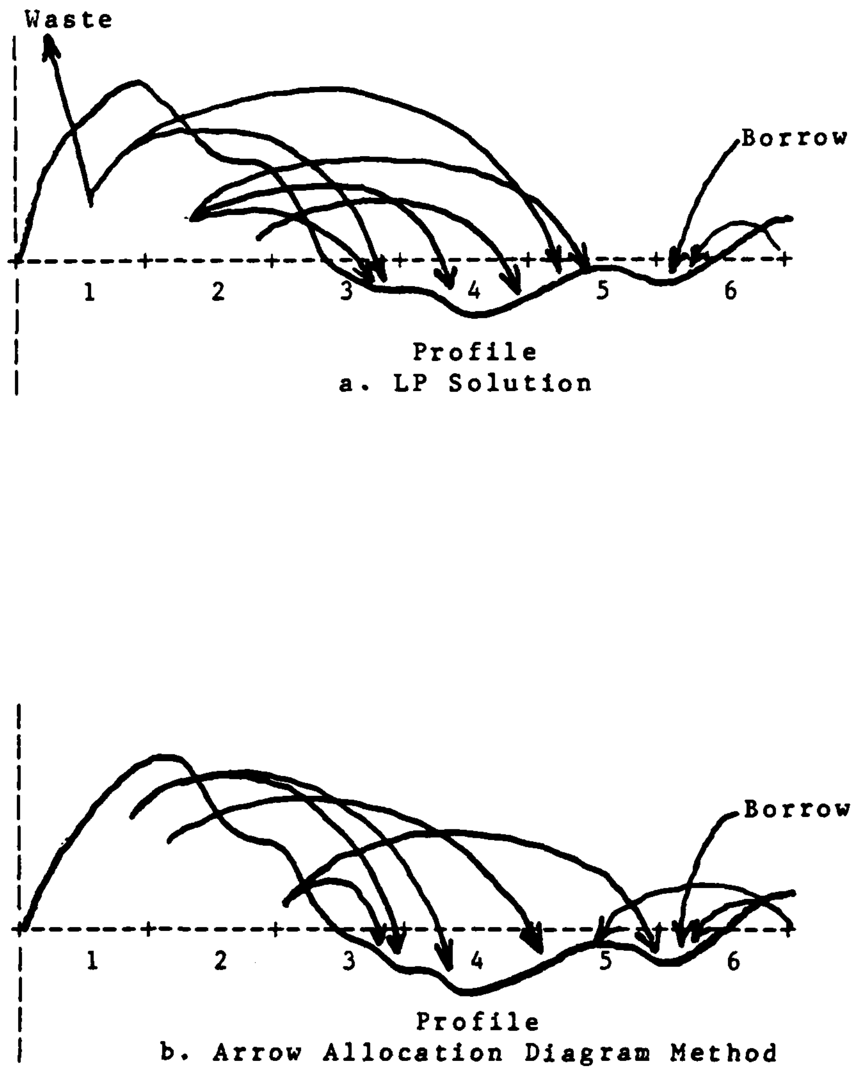

FIGURE 6-4 Earthwork Distribution for Example Problem

TABLE 6-9

Approximate Cost Estimate
for Example Problem

Variable	Qty.	Coef.	Subtotal
X14E	26.7	2553	$68,165.10
X14R	13.3	5118	68,069.40
X13E	9.3	2188	20,348.40
X25E	63.0	2553	160,839.00
X25R	26.0	5118	133,068.00
X65R	1.0	4078	4,078.00
X33E	14.2	1641	23,302.20
X33R	6.5	3818	24,817.00
X36E	26.3	2553	67,143.90
X66E	31.5	1641	51,691.50
X66R	18.5	3818	70,633.00
XB6E	3.7	1669	6,175.30
	-----		----------
Total	240.0		$698,330.80

$$\text{TUC} = \frac{\$698{,}330.80}{240{,}000 \text{ BCY}} = \$2.91/\text{BCY}$$

$$\text{Avg Haul} = \frac{155.3 \times 3 + 9.3 \times 2 + 4.7 \times 1 + 70.7 \times .5}{.240}$$

$$= 2185 \text{ ft.}$$

TABLE 6-10

Haul-Mass Data
for
Example Problem

1	2	3	4	5	6	7	8
Stations	Excav.(BCY) E/R	Embankment ccy	Excav.(CCY) E/R	Excess Embank (-)	Excess Excav. (+)	Mass Curve Ordinate	Qty. of Rock(ccy)
0.00-- 10+00	40 10	--	36.0 13.3	--	49.3	49.3	13.3
10+00-- 20+00	70 20	--	63.0 26.0	--	89.0	138.3	26.0
20+00-- 30+00	45 5	30	40.5 6.5	--	17.0	155.3	6.5
30+00-- 40+00	--	40	--	40	--	115.3	--
40+00-- 50+00	-- --	90	--	90	--	25.3	--
50+00-- 60+00	35 15	80	31.5 19.5	29	--	-3.7	19.5
Totals	240	240	236.3	159	155.3		65.3

	Proposed System	Traditional Estimate
Total Unit Cost ($/BCY)	$2.33-2.62	$2.91
50th percentile	$2.48	Unknown
68th percentile	$2.51	Unknown
95th percentile	$2.57	Unknown
Avg Haul Distance	1610 feet	2185 feet

The proposed system indicates a lower cost estimate (between 11 and 25% depending on the chosen value) due to the optimum distribution selected by the LP solution. It should be noted, however, that the proposed system's solution involves the movement of 270,020 BCY versus 240,000 BCY for the traditional estimate. A more meaningful comparison is to consider the total cost $629,147-$707,452 for the proposed system versus $698,331 for the traditional estimate. The range of $78,305 resulting from the proposed system brackets the traditional estimate and allows the decision-maker to choose a specified level of risk. The proposed system's distribution results in an average haul length that is some 575 feet less than that of the traditional estimate. Most importantly, the proposed system allows the user to select a unit cost estimate from a statistically valid range of values.

System Limitations

Although the proposed system was designed to account for a number of earthwork construction situations, it is important to amplify some of the system's limitations. Next is a description of certain construction circumstances that are not addressed by the proposed system.

The system accomodates both earth and rock material but makes no provision for unsuitable material (Note that unsuitable material is defined as material which, due to water and/or material content, cannot be used for embankment). For example, a highway designed to cross a swamp or a body of water would probably involve unsuitable material that must be "wasted" rather than transported to a fill area.

Also, the proposed system only applies to class 1 type excavation. Highway construction typically involves other types of excavation (backfilling around bridges and retaining walls, for example) incidental to the overall project. The system was not designed to handle these situations.

Finally, the system was developed under the assumption that the haul route is not restricted (i.e., material can be hauled from any cut to any fill). Certain projects (such as those involving river or canyon crossings, for example), however, physically restrict haul routes until the appropriate structures are complete. The system can only handle such situations by considering each section with unrestricted haul as a separate project (i.e., either side of a river, for example).

The foregoing discussion is not an exhaustive description of the system's limitations. It does point out, however, the type of construction realities that can not and should not be estimated by using the proposed system. As with any engineering estimate, judgement and experience are the key factors that must temper any attempt at "blind application" of this estimating tool.

System Programming

The proposed system was programmed in the APL language even though more common languages, such as FORTRAN or BASIC, could have been chosen. This section briefly summarizes why APL was chosen as the program language and points out the advantageous features of APL. The reader interested in the specifics of the programming is referred to Appendix B.

The APL Language

APL is an acronym for A Programming Language, a language that was invented by Kenneth Iverson in the early 1960's. The language is powerful, interactive, concise -- and under-used by the engineering community. It can perform all of the functions of the more traditional languages and usually with significantly less coding. The obvious drawback is that the system designer (Note: not the user) must become familiar with a new language that contains several "foreign" symbols and rules that are unlike FORTRAN or BASIC. This, quite possibly, is why APL has not yet caught on in the scientific community. Nevertheless, once learned, APL affords one the ability to create a matrix of any size and dimension, invert it, rotate it, or perform an arithmetic operation on it, each with a single command.

Aside from its inherent mathematical power, APL was chosen as the language for the proposed system because it posesses the most flexible ability to create a user-friendly program. In essence, any APL program can be written with a "built-in" user's manual so the first-time user will not be over-whelmed with new terms or symbols. More importantly, the user does not need to know anything about APL in order to use the system. In fact, job control language (JCL) is virtually non-existent in APL and the potential user need only know how to log-on, assuming his computer installation has an APL system, in order to use the proposed system.

Summary

This chapter has presented the proposed earthwork estimating system. Initially the assumptions of the proposed system were listed. Next, an explanation of how the models were integrated within the system was presented, followed by a detailed description of an example problem. Finally, the APL programming language, used in the proposed system, was briefly described along with reasons why it was selected in lieu of more common languages, such as FORTRAN or BASIC.

The next chapter presents a case study involving a recently completed highway project in Pennsylvania. The proposed system will be used to estimate the project and the results will be compared to both traditional estimates and the actual estimates used in the project.

CHAPTER SEVEN

CASE STUDY

This chapter applies the proposed system to an actual highway construction project. It begins by describing the $17 million project and then proceeds to illustrate how the proposed system would estimate the earthwork cost as opposed to other available methods. Finally, the results of the alternative estimates are compared to that of the proposed system.

Project Description

The project under study was located in central Pennsylvania. It consisted of constructing a four-lane concrete highway section approximately 3 miles in length. The earthwork volume involved in this project consisted of almost 3,000,000 cubic yards of earth and rock. In order to put this quantity in perspective -- consider the area of a football field, 100 yards long by 53 1/3 yards wide. If, in some manner, the quantity of material involved in this project were to be placed uniformly over a football field, the resulting pile would extend almost 1700 feet or one-third of a mile in height! Expressed horizontally, the volume of material involved in this project is enough to place a roadway (24 feet wide by 6 inches deep) extending from Harrisburg, Pa. to Omaha, Ne.!

Obviously, the earthwork volume under consideration is large by almost any standard. It is interesting to note that although the nation's interstate system is essentially complete, projects, such as the one under study, still exist. The reason is that state highway departments continue to improve traffic flow by construction of bypass and relocation routes to upgrade old highways.

PennDOT Estimate

The PennDOT District responsible for this project chose to use a consultant to prepare the cost estimate. This section summarizes the preparation of the cost estimate using the procedural steps outlined in Chapter Three. Detailed background data can be found in Appendix B.

Determination of Quantities

The soil data consists of test borings (Table 7-1), the District Engineer's Report, and the grading analysis summary. From this information the estimated quantitv of rock and swell/shrinkage factors were determined. Table 7-2 summarizes the District Engineer's Report and the grading analysis summary. It was estimated that there would be a total of approximately 38 percent rock, primarily shale and sandstone, in the earthwork.

Figure 7-1 shows the plan and haul-mass diagram for the project. A profile was not included because the earthwork sections include a partial cloverleaf interchange (sections 3 thru 5) and secondary roads (sections 4, 5, 6, and 8 thru

TABLE 7-1

Test Boring Data

Hole No.	Station	Offset (ft.) Left	Offset (ft.) Right	Depth (ft.)	Significant Information
1.	0+00	140		55.0	continuous sandstone beyond 11 ft. depth
2.	6+00	30		56.0	fractured shale beyond 12 ft. depth
3.	10+00	50		63.0	sandstone and shale beyond 10 ft. depth
4.	12+00		30	57.0	sandstone and shale beyond 12 ft. depth
5.	50+75	40		55.0	shale beyond 10 ft. depth
6.	50+75	40		72.0	sandstone down to total boring depth
7.	94+75		58	180.0	shale, coal, and sandstone beyond 10 ft. depth
8.	115+33	40		61.0	sandstone beyond 11 ft. depth

TABLE 7-1 (Continued)

Test Boring Data

Hole No.	Station	Offset (ft.) Left	Offset (ft.) Right	Depth (ft.)	Significant Information
9.	54+68	35		115.0	coal, sandstone, and shale beyond 14 ft. depth
10.	57+63		WB centerline	68.5	shale and sandstone beyond 11 ft. depth
11.	1+00		50	47.0	sandstone beyond 10 ft. depth
12.	1+00	145		56.8	shale and sandstone beyond 6 ft. depth
13.	5+00		54	50.0	shale and sandstone beyond 11 ft. depth
14.	5+00	145		36.0	shale and sandstone beyond 2 ft. depth
15.	9+00		54	51.5	sandstone and shale beyond 12 ft. depth
16.	9+00	145		31.0	shale and sandstone beyond 14 ft. depth

TABLE 7-2

Summary of Quantity Data by Section

Station	Section	Total Quantity (BCY)[1] (Rock Quantity/% of Total)	Shrinkage Factor[2]
0+00- 10+00-	1	378,527 (227,116/60)	.96
10+00- 20+00	2	221,603 (88,641/40)	.91
20+00- 30+00	3	143,402 (14,340/10)	.88
30+00- 40+00	4	367,983 (73,597/20)	.89
40+00- 50+00	5	667,113 (266,845/40)	.94
50+00- 60+00	6	397,370 (198,685/50)	.95
60+00- 70+00	7	0	
70+00- 80+00	8	788 (0/0)	.85
80+00- 90+00	9	6,720 (0/0)	.85

TABLE 7-2 (Continued)

Summary of Quantity Data by Section

Station	Section	Total Quantity (BCY)[1] (Rock Quantity/% of Total)	Shrinkage Factor[2]
90+00-100+00	10	5,939 (0/0)	.85
100+00-110+00	11	9,905 (0/0)	.85
110+00-120+00	12	6,439 (0/0)	.85
120+00-130+00	13	45,493 (0/0)	.85
130+00-140+00	14	549,937 (192,478/35)	.90
Total		2,801,219 (1,061,702/38)	

NOTES: 1. Includes earthwork of interchange and secondary roads.

2. Represents an average for all materials.

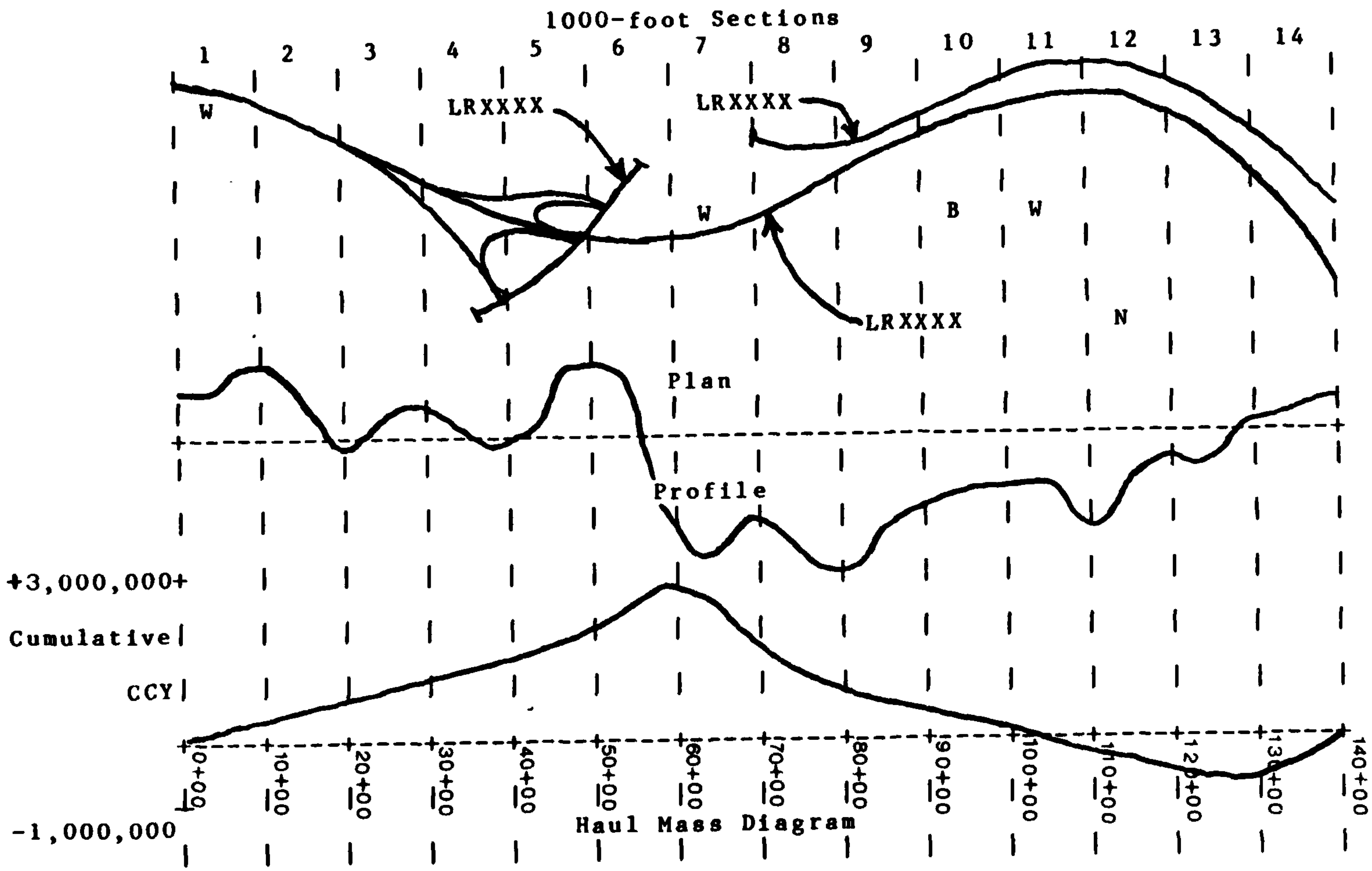

FIGURE 7-1 Plan and Haul-Mass Diagram

14). Tables are included in Appendix B for the haul-mass data as well as for the profile of the eastbound lanes of LR1101.

Determination of Cut/Fill Distribution

The haul-mass diagram shows that there are two major balanced sections with approximately 17,500 ccy of waste at station 140+00. The centers of mass of cut occur at stations 40+00 and 135+00. The overall average haul was calculated as follows:

$$\text{Total Avg Haul} = \frac{\text{Qty Section 1} \times \text{haul} + \text{Qty Section 2} \times \text{haul}}{\text{Total Qty}} \qquad (64)$$

$$= \frac{(1{,}893{,}724)(4{,}000) + (430{,}720)(2{,}000)}{2{,}324{,}444}$$

$$= \underline{3{,}629 \text{ ft.}}$$

Determination of Fleet Costs

The project was estimated under the assumption that only loader-truck fleets would be used by the contractor. (Actually, the contractor used a combination of loader-truck and scraper fleets). Table 7-3 is a summary of the fleet costs in dollars per hour. The cost data was obtained from the "Blue Book" (28th edition of Rental Rates published by Associated Equipment Distributors).

TABLE 7-3

Summary of Fleet Costs

1. Excavation

EQUIPMENT

Type	Rental, Fuel, and Oil ($/day)		
	Earthwork Classification		
	Earth (62%)	Hard Shale (14%)	Solid Rock (24%)
1-4cy Loader (shovel)	275.16	275.16	275.16
1-Bulldozer	285.12	285.12	285.12
3-Rollers	223.23	223.23	223.23
1-Grader	203.93	203.93	203.93
1-600 cfm Compressor		80.05	80.05
Jackhammers at $4.68/day		(2) 9.36	(4) 18.72
Air Hose at $1.08/section		(4) 4.32	(8) 8.64
Sub-Total	987.44	1,081.17	1,094.85
Labor	1,042.91	1,381.75	1,631.16
Total	2,030.35	2,462.92	2,726.01

2. Haul

30-35 cy truck (off-road) $453.08 per day

3. Explosive Supplies $225.50 per day

Determination of Fleet Productivity

Productivity was estimated from data compiled by the consultant. Table 7-4 summarizes the productivity estimate. The estimated values were obtained from PennDOT charts that relate productivity to earthwork classification and an index value obtained by dividing the total excavation by the total length of cut sections.

Determination of Project Unit Cost

The calculations shown in Table 7-5 use data contained in Tables 7-3 and 7-4. As indicated in the notes below Table 7-5, an error was found by the writer in the unit cost estimate because the costs of only one truck were included and this is not realistic due to the differences in shovel and truck productivities. The PennDOT District, upon reviewing the consultant's total unit price estimate (including profit and overhead) of $1.75 per cy decided to increase this amount and subsequently used $2.00 per cy for their final unit cost estimate.

Contractor Estimate

This section summarizes the contractor's unit cost estimate for earthwork. It follows the procedural steps presented in Chapter Three for earthwork contractors. Additional data is located in Appendix C.

TABLE 7-4

Productivity Estimates

Earthwork Classification/Percentage		Productivity (BCY/day/unit) (for a 3/4 cy shovel)
1. Excavation	(% of total)	
Earth	36%	760
Clay	8%	600
Soft Shale	18%	690
Hard Shale	14%	495
Solid Rock	24%	270

2. Haul
   11 min cycle time
   60 min ÷ 11 min/trip = 5.45 trips/hr
   20 cy per trip
   20 cy/trip x 5.45 trips/hr x 8 hr/day = 872 BCY/day/unit

3. Shovel Progress	Qty ÷ Productivity x % of total
Earth	2,801,219 ÷ 760 x .36 = 1,326.9
Clay	2,801,219 ÷ 600 x .08 = 373.5
Soft Shale	2,801,219 ÷ 690 x .18 = 730.8
Hard Shale	2,801,219 ÷ 495 x .14 = 792.3
Solid Rock	2,801,219 ÷ 270 x .24 = 2,490.0
	5,713.5 days

For 4 cy shovel .75 ÷ 4 x 5,715.5 = 1,071.3 days

cy per day = 2,801,219 cy ÷ 1,071.3 days = 2,614 cy/day

TABLE 7-5

Calculation of Project Unit Cost

Earthwork Classification	Equipment and Labor	Calculation $/day	
Earth, clay, and shale,62%	$2,030.35/day	.62 x 2,030.35 =	$1,258.82
Hard shale,14%	$2,462.92/day	.14 x 2,462.92 =	344.81
Solid rock,24%	$2,726.01	.24 x 2,726.01 =	654.24
Explosive Supplies			225.50
			$2,483.37

Unit Cost for Excavation:
$2,483.37/day ÷ 2,614 cy/day = $0.95/cy

Unit Cost for Hauling:
$453.08/day ÷ 872 cy/day = $0.52/cy

Total Unit Cost = $1.47/cy

NOTE: 1. Only the direct unit costs are included.

2. The estimate is based on one shovel and 1 truck. Comparing daily productivities, one finds

Shovel -- 2,614 cy/day
(See Table 7-4)
Truck -- 872 cy/day

Number of trucks required: 2,614 ÷ 872 = 3.0

NOTE: This is could be an error in the consultant's estimate.

Field Drilling

The contractor decided to supplement the test borings provided by PennDOT with his own field tests. Table 7-6 presents the field drilling log for seven test holes. All of the test holes are located in the vicinity of the partial cloverleaf intersection since this is the area requiring the greatest volume of cut.

The material description is similar to the PennDOT borings but the contractor also distinguished medium hard and hard rock depth. These are used to differentiate between the amount of explosives needed for a "soft" versus "hard" blasting estimate.

Plotting Rock Lines -- Calculation of Volumes

The limited number of borings (23 total) restricts one to plotting rock lines for only two of the major cut areas. The first is on the western boundary (Sta. 0+00-10+00) and the second is in the vicinity of the cloverleaf intersection (Sta. 47+00-54+00). Together, these two areas represent about one fourth of the total excavation but, more significantly, they account for the sections having the deepest cuts. Sketches of the cross sections and related calculations to estimate the rock quantities are included in Appendix C. Table 7-7 summarizes the estimated rock quantities.

TABLE 7-6

Field Drilling Log

Hole No.	Station/ Location	Depth/Description		Drilling Production (6 in. dia. bit) Depth[1]	Rate[2]
1	53+50	00-07	cover		
	EB C	07-23	brown shale soft		
		23-27	black shale	25'	
		27-38	gray shale		5'/min
		38-44	black shale hard	50'	
		44-45	coal	50'	
		45-53	black shale hard		4'/min
		53-60	sandy shale	60'	
2	54+00	00-10	cover		
	WB-140L	10-25	brown shale	25'	
		25-35	black shale		6'/min
		35-45	gray shale	50'	
		45-48	shale and sandstone	50'	
		48-49	coal		4'/min
		49-53	gray shale hard	75'	
		53-58	sandstone		
		58-75	sandy shale		
3	49+00	00-10	cover		
	WB-40R	10-15	brown shale		
		15-40	gray shale		
		40-47	sandy shale med. hard		
		47-48	coal		
		48-56	sandy shale		
		56-65	sandstone		
		65-75	sandy shale hard		
4	49+00	00-10	cover		
	EB-140L	10-15	brown shale		
		15-20	gray shale		
		20-25	gray shale med. hard		
		25-47	sandy shale		
		47-48	coal		
		48-55	sandy shale hard		

TABLE 7-6 (Continued)

Field Drilling Log

Hole No.	Station/ Location	Depth/Description		Drilling Production (6 in. dia. bit)
5	406+78	00-10	cover	No data available
	Ramp CD C	10-25	brown shale	
		25-35	brown sandy shale	
		35-41	black shale	
		41-42	coal	
		42-50	black shale hard	
6	47	00-10	cover	
	WB-40L	10-25	brown shale	
		25-32	sandy shale med. hard	
		32-40	sandy shale hard	
		40-41	coal	
		41-50	sandy shale hard	
7	47	00-10	cover	
	WB-160L	10-25	brown shale	
		25-32	sandy shale med. hard	
		32-40	sandy shale hard	
		40-41	coal	
		41-50	sandy shale hard	

NOTES:

1. Depth is measured from ground level and extends down to the proposed grade.
2. Rate indicates the drill bit penetration rate in ft per minute.

TABLE 7-7

Estimated Rock Quantities

Section	Earth (% Total)	Rock (% Total)	Total	Remarks
1+00- 9+00	125,222 (50%)	123,304 (50%)	248,526	Not enough info to determine soft vs. hard rock
47+00- 54+00	230,044 (65%)	80,731 (23%) soft 42,787 (12%) hard	353,562	Adequate soil info. available

NOTES: 1. Assuming the above two sections are representative of the total cut, calculate total percentage of rock.

$$\text{rock} = \frac{(\text{Vol.}_{\text{sect 1}})(\%\text{rock}_{\text{sect 1}})+(\text{Vol.}_{\text{sect 2}})(\%\text{rock}_{\text{sect 2}})}{(\text{Vol.}_{\text{sect 1}})+(\text{Vol.}_{\text{sect 2}})}$$

$$= \frac{(248{,}526)(.50)+(353{,}562)(.35)}{248{,}526+353{,}562}$$

= 0.41 ---> use 40% rock

2. Assume soft/hard rock distribution follows the section 47+00-54+00 and round-up percentages.

% soft rock -- 25
% hard rock -- 15

Determining Cut/Fill Distribution

Table 7-8 is the arrow allocation diagram that the contractor used in determining the cut/fill distribution. Note that the quantities are in BCY units and that material is planned to be wasted in the first section (Sta. 0+00-10+00).

Determining Fleet Composition/Costs

The contractor estimated the project with the assumption that three separate fleets were required. Two loader-truck and one scraper fleet were estimated on the basis of a 9-hour workday. In addition, it was also planned that one of the loader-truck and the scraper fleet would work a 9-hour night shift. Table 7-9 is a summary of the costs for these three fleets as well as for the drilling and blasting fleets.

Applying Production Rates

The approach used by the contractor was to rely on extensive historical data to estimate fleet production. For the loader-truck fleets, the contractor knew that his equipment could move between 4100 and 4500 BCY per 9-hour shift. He chose a production estimate of 4300 BCY per shift for day and 4150 BCY per shift for night operations. For the scraper fleet, past data showed production ranging from 5600 to 6000 BCY per shift. He chose production values of 6000 BCY and 5000 BCY. respectively, for the day and night shift scraper operations. Table 7-10 summarizes the fleet

TABLE 7-8

Arrow Allocation Diagram

Stations (100 ft.)	Excavation (cut BCY)		Waste (BCY)	Embankment (fill BCY)
0+00-10+00	378,527	--->	333,270	
		---> 11,137		
		---> 34,120		
10+00-20+00	221,603	---> 3,169		11,137
		---> 34,541		
		---> 48,300		
		---> 16,862		
		---> 118,731		
20+00-30+00	143,402	---> 143,402		37,289
30+00-40+00	385,020	---> 162,229		34,541
		---> 222,791		
40+00-50+00	634,172	---> 335,562		48,300
		---> 298,610		
50+00-60+00	418,548	---> 249,072		16,862
		---> 169,476		
60+00-70+00	1,899	---> 1,899		424,362
70+00-80+00	11,229	---> 11,229		558,353
80+00-90+00	9,696	---> 9,696		547,682
90+00-100+00	15,017	---> 15,017		224,633
100+00-110+00	45,537	---> 17,316		249,030
		---> 28,221		
110+00-120+00	43,521	---> 43,521		270,505
120+00-130+00	98,608	---> 98,608		138,117
130+00-143+85	534,493	---> 78,680		47,191
		---> 270,505		
		---> 138,117		
		---> 47,191		
Total	2,941,272			2,608,002
			(waste)	+ 333,270
				2,941,272

Avg. Haul Dist. = 3,134 ft.
(See Appendix C for Calculation)

TABLE 7-9

Summary of Contractor Fleet Costs

EQUIPMENT

	Type	Rental, Fuel, and Oil ($/day)		Labor ($/day)
1.	Excavation Fleet 1		(Laborers)	204.44
1	475 Loader(front-end)	788.10		159.72
1	D9 Dozer	667.20		148.83
1	D8 Dozer	496.30		148.83
1	Roller	233.60		121.97
1	Grader	304.50		148.84
4	Trucks (35 cy, off-road) at $474.00 each	1,896.00		446.88
1/2	Water tanker	52.60		46.24
1	Pick-up	12.00	(Foreman)	124.96
	Sub-total	$4,450.30		$1,550.70
	Total (rental + labor)		$6,001.00/day	
	Fleet 2		(Laborers)	204.44
1	992 Loader(front-end)	888.10		159.72
1	D9 Dozer	667.20		148.83
1	D8 Dozer	496.30		148.83
1	Roller	233.60		121.97
1	Grader	304.50		148.84
4	Trucks (35 cy, off-road) at $474.00/each	1,896.00		446.88
1/2	Water tanker	52.60		46.24
1	Pick-up	12.00	(Foreman)	124.96
	Sub-total	$4,550.30		$1,550.70
	Total (rental + labor)		$6,101.00/day	

TABLE 7-9 (Continued)

Summary of Contractor Fleet Costs

	Type	Rental, Fuel, and Oil ($/day)		Labor ($/day)
	Fleet 3		(Laborers)	204.44
5	641 Scrapers (28 cy) 2 at $518.80/each 3 at $568.80/each	2,744.00		689.70
3	D9 Dozers at $582.30/each	1,746.90		446.49
1	D8 Dozer	458.90		148.83
1	D8 Compactor	368.80		148.83
1	Roller	169.20		121.97
1	Grader	299.00		148.83
1/2	Water tanker	52.60		46.24
1	Pick-up	12.00	(Foreman)	124.96
	Sub-total	$5,851.40		$2,080.29
	Total (rental + labor)		$7,931.69/day	

2. Drilling and Blasting

DM-45 Fleet	Rental, Fuel and Oil, Bits and Explosives		Labor
Drill	991.77		315.00
Load	1,858.26		717.00
Shoot	------		217.96
Sub-total	$2,850.04		$1,249.96
Total		$4,100/day	

Air-Trac Fleet			
Drill	1,157.25		315.00
Load	6,492.79		717.00
Shoot	------		217.96
Sub-total	$7,650.04		$1,249.96
Total		$8,900/day	

TABLE 7-10

Production Estimates

1. Excavation Fleet

(1) Shift	(2) Fleet	(3) Total Fleet Cost ($/shift)	(4) Fleet Production (BCY/shift)	(5) Fleet Unit Cost ($/BCY) Col.3 ÷ Col.4)
Day	475 Loader	$6,001.00	4,300	$1.3956
Day	992 Loader	6,101.00	4,300	1.4188
Night	992 Loader	6,101.00	4,150	1.4701
Day	Scraper	7,931.69	6,000	1.3219
Night	Scraper	7,931.69	5,000	1.5863

2. Drilling and Blasting Fleet

Fleet	Total Fleet Cost ($/shift)	Fleet Production (BCY/shift)	Fleet Unit Cost ($/BCY) Col.3 ÷ Col.4)
DM-45 Drill	$4,100.00	10,000	$0.41
Air-Trac Drill	8,900.00	10,000	0.89

production data and indicates the fleet unit cost which is used later in computing the total unit cost.

Determining Project Unit Cost

Table 7-11 summarizes the calculations used to estimate a total unit cost for the earthwork portion of this project. When the total direct unit cost of \$1.67/BCY was added to the indirect costs, profit, and mark-up, the total amount of \$2.28/BCY became the contractor's bid price.

Proposed System Estimate

In this section, the proposed estimating system is applied to the same project described earlier. It will follow the same steps used in estimating the example problem in Chapter Six. The estimate will be developed from the perspective of an experienced earthwork contractor who has historical cost and productivity data.

Quantity Take-Off

Table 7-12 summarizes the quantity data for the proposed system. Appendix D provides a description of how the quantities of rock in each cut section were estimated.

Calculation of Cost Coefficients

The notation used to define the variables consists of three numerals. The first number is the source or origin section of the roadway, the second number is the destination section, and the third number is the material classification and identifier for borrow and/or waste sites. The third

TABLE 7-11

Contractor Calculation of Unit Cost

(1) Shift	(2) Fleet	(3) Quantity (BCY/ shift)	(4) Fleet Unit Cost ($/BCY)	(5) Total Fleet Cost ($) (Col.3 x Col.4)
Day only	475 Loader	612,191	$1.40	$ 857,067
Day	992 Loader	578,574	1.42	821,575
Night	992 Loader	360,516	1.47	529,959
Day	Scraper	917,374	1.32	1,210,934
Night	Scaper	503,148	1.59	800,005
Total Volume		2,971,803		
Day only Drilling and Blasting Soft Shoot (.25 x 2,971,803)		742,951	0.41	304,610
Hard Shoot (.15 x 2,971,803)		445,770	0.89	396,735
Total				$4,920,885

Total Unit Cost = Total Fleet Cost - Total Volume

= 4,920,885 - 2,941,272

= $1.67/BCY

NOTE: Indirect costs, profit, mark-up, and bidding strategy accounted for an additional $0.61/BCY making the bid price $2.28/BCY.

TABLE 7-12

Proposed System Quantity Summary

Quantities of Cut/Fill (1000 BCY)

Section Number	Cut Earth	Cut Rock Mean	Cut Rock Std. Dev.	Cut Total	Fill
1	227.12	151.41	9.46	378.53	0.00
2	139.61	81.99	5.54	221.60	11.14
3	90.34	53.06	3.59	143.40	37.29
4	242.56	142.46	9.63	385.02	34.54
5	380.50	253.67	23.78	634.17	48.30
6	251.13	167.42	10.46	418.55	16.86
7	1.90	0.00	----	1.90	424.36
8	11.23	0.00	----	11.23	558.35
9	9.70	0.00	----	9.70	547.68
10	15.02	0.00	----	15.02	224.63
11	45.54	0.00	----	45.54	249.03
12	43.52	0.00	----	43.52	270.51
13	64.10	34.51	2.47	98.61	138.12
14	347.42	187.07	13.36	534.49	47.19
Total	1,869.69	1,071.59		2,941.28	2,608.00

	Swell Factor	Shrinkage Factor
Earth	1.25	.85
Rock	1.45	1.10

number will be between 1 and 5 with the following definitions:

1 = earth

2 = rock

3 = waste earth

4 = waste rock

5 = borrow (only earth assumed).

The following examples should clarify the notation.

Variable	Meaning
X(1,1,3)	The movement of earth from section 1 to a waste area located within the first 1000-foot section of the roadway.
X(3,11,2)	The movement of rock from section 3 to section 11 of the roadway.
X(9,8,5)	The movement of earth borrow from a site located within the ninth 1000-foot section of the roadway to the eighth section.
X(5,5,1)	The movement of earth (cut-to-fill) within the fifth 1000-foot section of the roadway.
X(6,4,2)	The movement of rock from section 6 to section 4.

Table 7-13 summarizes the cost data that was input for the case study problem. Refer to Appendix D for details of how the input costs were obtained. Note that the haul cost estimates were varied to reflect anticipated conditions, such as grade of haul road and a railroad crossing as well as variability in production rates. Figure 7-2 is a plan

TABLE 7-13

Summary of Input Cost Data

Excavation (including loading)		$ per 1000 BCY (3-value estimate)
Earth		390 437 517
Rock		634 667 766
Compaction (including unloading)		
Along Roadway:	Earth	263 282 311
	Rock	258 282 311
At Landfill:	Earth	47 94 118
	Rock	47 94 118
Haul		
Normal:	Earth or Rock	226 244 273
25% Higher:		282 306 343
50% Higher:		338 367 409
25% Lower:		169 183 202
10% Higher:		249 268 451
15% Lower:		192 207 231

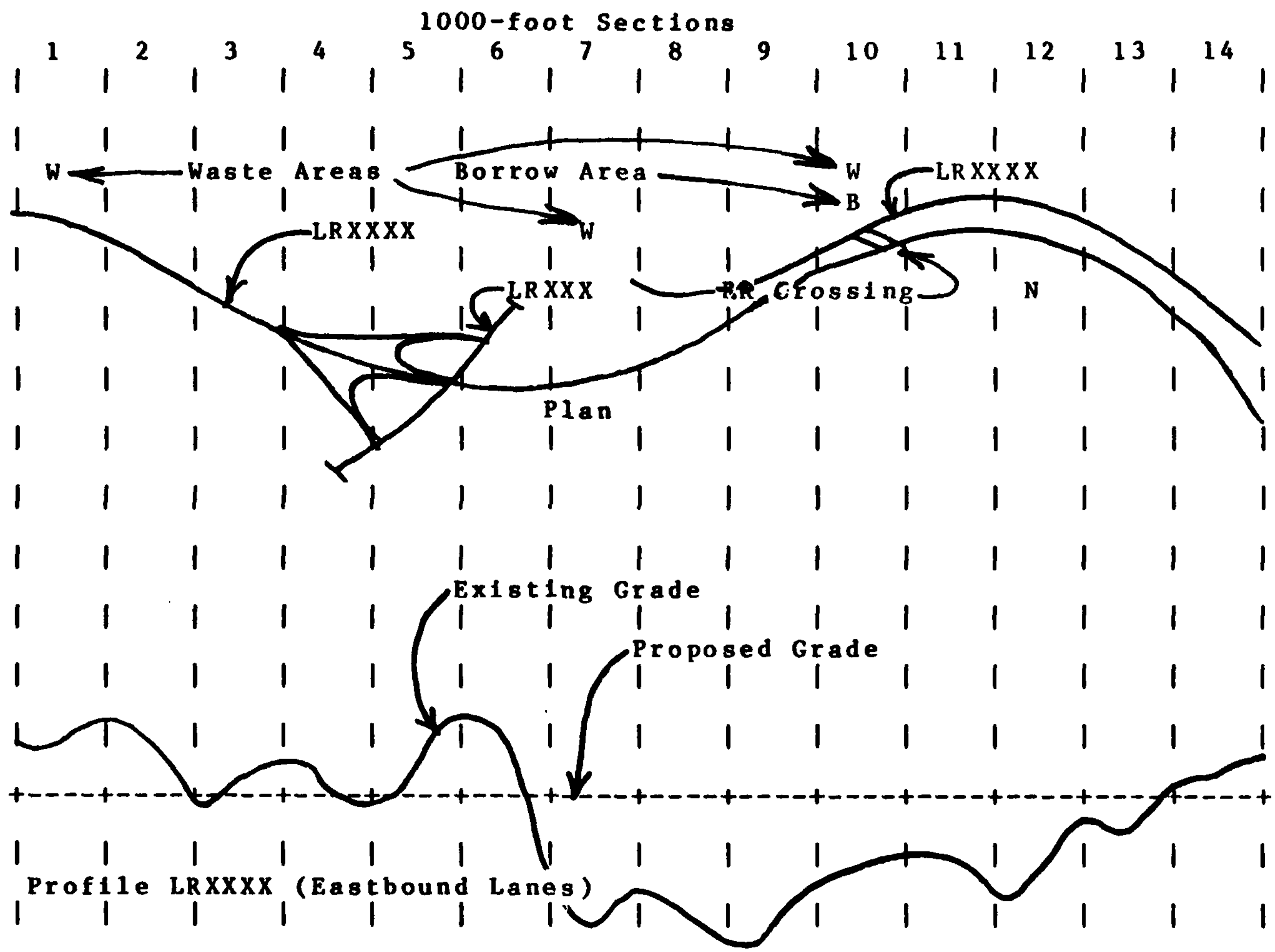

FIGURE 7-2 Plan and Typical Haul Profile

and profile (eastbound lanes) that helps illustrate why different haul estimates were used for variables in certain sections. For example, variables with a source section of 4 and a destination section of 5 or higher must contend with a steep incline at section 5 so these variables were assigned haul costs that were 25% higher than normal (Note: The percentage adjustments of haul cost input were determined thru consultation with the contractor who estimated and completed the project). Similar adjustments for grade were made for variables with a source in sections numbered 5, 6, 7, 9, and 14.

Finally, a railroad crossing is located at section 10 of the roadway. Due to the requirements for flagmen at this location, variables requiring movement through section 10 (i.e., X(9,11,1) for example) were adjusted with a 25% increase in haul costs. The complete listing of input costs for each variable as well as the calculated coefficients can be found in Appendix D.

LP Formulation

Using equation (45) presented in the last chapter, it is possible to consider as many as 480 variables (NVAR = 2 x 16 x 15) in this problem. However, the assumption that sections 7 thru 12 does not contain rock eliminates 90 variables (6 x 15) from consideration. The remaining 390 possible variables were narrowed to 233 by applying engineering judgement, such as not considering the movement of material between the extreme end sections of the roadway since haul lengths approaching two miles are rarely economical. The problem was formulated using the same techniques employed in the example problem illustrated in the last chapter. A complete listing of the formulation follows.

Cut Contraints. The following equations are the cut constraints:

$$\begin{aligned}
&X(1,1,3) + X(1,1,4) + X(1,2,1) + \\
&X(1,2,2) + X(1,3,1) + X(1,3,2) + \\
&X(1,4,1) + X(1,4,2) + X(1,5,1) + \\
&X(1,5,2) + X(1,6,1) + X(1,6,2) + \\
&X(1,7,1) + X(1,7,2) + X(1,8,2) + \\
&X(1,9,1) + X(1,9,2) + X(1,8,1) = 378.53
\end{aligned} \tag{65}$$

$$\begin{aligned}
&X(2,1,3) + X(2,1,4) + X(2,2,1) + \\
&X(2,2,2) + X(2,3,1) + X(2,3,2) + \\
&X(2,4,1) + X(2,4,2) + X(2,5,1) + \\
&X(2,5,2) + X(2,6,1) + X(2,6,2) + \\
&X(2,7,1) + X(2,7,2) + X(2,8,1) + \\
&X(2,8,2) + X(2,9,1) + X(2,9,2) + \\
&X(2,10,1) + X(2,10,2) = 221.60
\end{aligned} \tag{66}$$

$$\begin{aligned}
&X(3,1,3) + X(3,1,4) + X(3,2,1) + \\
&X(3,2,2) + X(3,3,1) + X(3,3,2) + \\
&X(3,4,1) + X(3,4,2) + X(3,5,1) + \\
&X(3,5,2) + X(3,6,1) + X(3,8,1) + \\
&X(3,10,1) + X(3,6,2) + X(3,8,2) + \\
&X(3,10,2) + X(3,7,1) + X(3,9,1) + \\
&X(3,11,1) + X(3,7,2) + X(3,9,2) + \\
&X(3,11,2) = 143.40
\end{aligned} \tag{67}$$

$$\begin{aligned}
&X(4,1,3) + X(4,1,4) + X(4,2,1) + \\
&X(4,2,2) + X(4,3,1) + X(4,3,2) + \\
&X(4,4,1) + X(4,4,2) + X(4,5,1) + \\
&X(4,5,2) + X(4,6,1) + X(4,6,2) + \\
&X(4,7,1) + X(4,7,2) + X(4,7,3) + \\
&X(4,7,4) + X(4,8,1) + X(4,8,2) + \\
&X(4,9,1) + X(4,9,2) + X(4,10,1) + \\
&X(4,10,2) + X(4,11,1) + X(4,11,2) + \\
&X(4,12,1) + X(4,12,2) = 385.02
\end{aligned} \tag{68}$$

$$\begin{aligned}
&X(5,1,3) + X(5,1,4) + X(5,2,1) + \\
&X(5,2,2) + X(5,3,1) + X(5,3,2) + \\
&X(5,4,1) + X(5,4,2) + X(5,5,1) + \\
&X(5,5,2) + X(5,6,1) + X(5,6,2) + \\
&X(5,7,1) + X(5,7,2) + X(5,7,3) +
\end{aligned}$$

$$\begin{aligned}
&X(5,7,4) + X(5,8,1) + X(5,8,2) + \\
&X(5,9,1) + X(5,9,2) + X(5,10,1) + \\
&X(5,10,2) + X(5,11,1) + X(5,11,2) + \\
&X(5,12,1) + X(5,12,2) + X(5,13,1) + \\
&X(5,13,2) = 634.17
\end{aligned} \tag{69}$$

$$\begin{aligned}
&X(6,3,1) + X(6,3,2) + X(6,4,1) + \\
&X(6,4,2) + X(6,5,1) + X(6,5,2) + \\
&X(6,6,1) + X(6,6,2) + X(6,7,1) + \\
&X(6,7,2) + X(6,7,3) + X(6,7,4) + \\
&X(6,8,1) + X(6,8,2) + X(6,9,1) + \\
&X(6,9,2) + X(6,10,1) + X(6,10,2) + \\
&X(6,11,1) + X(6,11,2) + X(6,12,1) + \\
&X(6,12,2) + X(6,13,1) + X(6,13,2) = 418.55
\end{aligned} \tag{70}$$

$$\begin{aligned}
&X(7,6,1) + X(7,7,1) + X(7,7,3) + \\
&X(7,8,1) + X(7,9,1) + X(7,10,1) + \\
&X(7,11,1) + X(7,12,1) = 1.90
\end{aligned} \tag{71}$$

$$\begin{aligned}
&X(8,7,1) + X(8,7,3) + X(8,8,1) + \\
&X(8,9,1) + X(8,10,1) + X(8,6,1) + \\
&X(8,11,1) + X(8,12,1) + X(8,13,1) = 11.23
\end{aligned} \tag{72}$$

$$\begin{aligned}
&X(9,7,1) + X(9,7,3) + X(9,8,1) + \\
&X(9,9,1) + X(9,10,1) + X(9,11,1) + \\
&X(9,11,3) + X(9,12,1) + X(9,13,1) = 9.70
\end{aligned} \tag{73}$$

$$\begin{aligned}
&X(10,8,1) + X(10,9,1) + X(10,10,1) + \\
&X(10,11,1) + X(10,11,3) + X(10,12,1) + \\
&X(10,13,1) + X(10,7,1) = 15.02
\end{aligned} \tag{74}$$

$$\begin{aligned}
&X(11,8,1) + X(11,9,1) + X(11,10,1) + \\
&X(11,11,1) + X(11,11,3) + X(11,12,1) + \\
&X(11,13,1) + X(11,14,1) + X(11,7,1) = 45.54
\end{aligned} \tag{75}$$

$$\begin{aligned}
&X(12,8,1) + X(12,9,1) + X(12,10,1) + \\
&X(12,11,1) + X(12,11,3) + X(12,12,1) + \\
&X(12,13,1) + X(12,14,1) + X(12,7,1) = 43.52
\end{aligned} \tag{76}$$

$$\begin{aligned}
&X(13,10,1) + X(13,11,1) + X(13,11,3) + \\
&X(13,12,1) + X(13,13,1) + X(13,14,1) + \\
&X(13,8,2) + X(13,9,2) + X(13,10,2) + \\
&X(13,11,2) + X(13,12,2) + X(13,13,2) + \\
&X(13,14,2) + X(13,8,1) + X(13,9,1) + \\
&X(13,7,1) + X(13,7,2) = 98.61
\end{aligned} \tag{77}$$

$$\begin{aligned}
&X(14,7,1) + X(14,7,2) + X(14,8,1) + \\
&X(14,8,2) + X(14,9,1) + X(14,9,2) + \\
&X(14,10,1) + X(14,10,2) + X(14,11,1) + \\
&X(14,11,2) + X(14,11,3) + X(14,11,4) + \\
&X(14,12,1) + X(14,12,2) + X(14,13,1) + \\
&X(14,13,2) + X(14,14,1) + X(14,14,2) = 534.49
\end{aligned} \tag{78}$$

Assuming a 5 percent chance of constraints being violated, the chance constraints for rock quantity are calculated with the formula,

$$Z = \frac{b_i - E(b_i)}{b_i} \quad (Z = +1.65 \text{ from normal curve tables}) \qquad (79)$$

<u>Rock Quantity Cut Constraints</u>. The following equations are the chance constraints for the rock quantity:

Section 1:

$$\frac{X(1,1,4) + X(1,2,2) + X(1,3,2) + X(1,4,2) - 151.41}{9.46} \geq +1.65$$

$$X(1,1,4) + X(1,2,2) + X(1,3,2) + X(1,4,2) + X(1,5,2) + X(1,6,2) + X(1,7,2) + X(1,8,2) + X(1,9,2) \geq 167.02 \qquad (80)$$

Section 2:

$$\frac{X(2,1,4) + X(2,2,2) + X(2,3,2) + X(2,4,2) + X(2,5,2) - 81.99}{5.54} \geq +1.65$$

$$X(2,1,4) + X(2,2,2) + X(2,3,2) + X(2,4,2) + X(2,5,2) + X(2,6,2) + X(2,7,2) + X(2,8,2) + X(2,9,2) + X(2,10,2) \geq 91.13 \qquad (81)$$

Section 3:

$$\frac{X(3,1,4) + X(3,2,2) + X(3,3,2) + X(3,4,2) + X(3,5,2) - 53.06}{3.59} \geq +1.65$$

$$X(3,1,4) + X(3,2,2) + X(3,3,2) + X(3,4,2) + X(3,5,2) + X(3,6,2) + X(3,8,2) + X(3,10,2) + X(3,7,2) + X(3,9,2) + X(3,11,2) \geq 58.98 \qquad (82)$$

Section 4:

$$\frac{X(4,1,4) + X(4,2,2) + X(4,3,2) + X(4,4,2) + X(4,5,2) + X(4,6,2) + X(4,7,2) + X(4,7,4) + X(4,8,2) + X(4,9,2) - 142.46}{9.63} \geq +1.65$$

$$X(4,1,4) + X(4,2,2) + X(4,3,2) + X(4,4,2) + X(4,5,2) + X(4,6,2) + X(4,7,2) + X(4,7,4) + X(4,8,2) + X(4,9,2) + X(4,10,2) + X(4,11,2) + X(4,12,2) \geq 158.35 \quad (83)$$

Section 5:

$$\frac{X(5,1,4) + X(5,2,2) + X(5,3,2) + X(5,4,2) + X(5,5,2) + X(5,6,2) + X(5,7,2) + X(5,7,4) + X(5,8,2) + X(5,9,2) + X(5,10,2) + X(5,11,2) - 253.67}{23.78} \geq +1.65$$

$$X(5,1,4) + X(5,2,2) + X(5,3,2) + X(5,4,2) + X(5,5,2) + X(5,6,2) + X(5,7,2) + X(5,7,4) + X(5,8,2) + X(5,9,2) + X(5,10,2) + X(5,11,2) + X(5,12,2) + X(5,13,2) \geq 292.91 \quad (84)$$

Section 6:

$$\frac{X(6,3,2) + X(6,4,2) + X(6,5,2) + X(6,6,2) + X(6,7,2) + X(6,7,4) + X(6,8,2) + X(6,9,2) + X(6,10,2) + X(6,11,2) + X(6,12,2) + X(6,13,2) - 167.42}{10.46} \geq +1.65$$

$$X(6,3,2) + X(6,4,2) + X(6,5,2) + X(6,6,2) + X(6,7,2) + X(6,7,4) + X(6,8,2) + X(6,9,2) + X(6,10,2) + X(6,11,2) + X(6,12,2) + X(6,13,2) \geq 184.69 \quad (85)$$

Section 13:

$$\frac{X(13,9,2) + X(13,10,2) + X(13,11,2) + X(13,11,4) + X(13,12,2) + X(13,13,2) + X(13,14,2) + X(13,7,2) + X(13,8,2) - 187.07}{13.36} \geq 1.65$$

$$X(13,7,2) + X(13,8,2) + X(3,9,2) + X(13,10,2) + X(13,11,2) + X(13,11,4) + X(13,12,2) + X(13,13,2) + X(13,14,2) \geq 38.59 \quad (86)$$

Section 14:

$$\frac{X(14,7,2) + X(14,8,2) + X(14,9,2) + X(14,10,2) + X(14,11,2) + X(14,11,4) + X(14,12,2) + X(14,13,2) + X(14,14,2) - 187.07}{13.36} \geq +1.65$$

$$X(14,7,2) + X(14,8,2) + X(14,9,2) + X(14,10,2) + X(14,11,2) + X(14,11,4) + X(14,12,2) + X(14,13,2) + X(14,14,2) \geq 209.11 \quad (87)$$

Fill Constraints. The fill constraints are calculated in the next series of equations:

Section 1: 0 fill

Section 2:

$$.85X(1,2,1) + 1.1X(1,2,2) + .85X(2,2,1) + 1.1X(2,2,2) + .85X(3,2,1) + 1.1X(3,2,2) + .85X(4,2,1) + 1.1X(4,2,2) + .85X(5,2,1) + 1.1X(5,2,2) = 11.14 \quad (88)$$

Section 3:

$$.85X(1,3,1) + 1.1X(1,3,2) + .85X(2,3,1) + 1.1X(2,3,2) + .85X(3,3,1) + 1.1X(3,3,2) + .85X(4,3,1) + 1.1X(4,3,2) + .85X(5,3,1) + 1.1X(5,3,2) + .85X(6,3,1) + 1.1X(6,3,2) = 37.29 \quad (89)$$

Section 4:

$$.85X(1,4,1) + 1.1X(1,4,2) + .85X(2,4,1) + 1.1X(2,4,2) + .85X(3,4,1) + 1.1X(3,4,2) + .85X(4,4,1) + 1.1X(4,4,2) + .85X(5,4,1) + 1.1X(5,4,2) + .85X(6,4,1) + 1.1X(6,4,2) = 34.54 \quad (90)$$

Section 5:

$$
\begin{aligned}
&.85X(2,5,1) + 1.1X(2,5,2) + \\
&.85X(3,5,1) + 1.1X(3,5,2) + \\
&.85X(4,5,1) + 1.1X(4,5,2) + \\
&.85X(5,5,1) + 1.1X(5,5,2) + \\
&.85X(6,5,1) + 1.1X(6,5,2) + \\
&.85X(1,5,1) + 1.1X(1,5,2) = 48.30
\end{aligned} \tag{91}
$$

Section 6:

$$
\begin{aligned}
&.85X(4,6,1) + 1.1X(4,6,2) + \\
&.85X(5,6,1) + 1.1X(5,6,2) + \\
&.85X(6,6,1) + 1.1X(6,6,2) + \\
&.85X(7,6,1) + .85X(1,6,1) + \\
&1.1X(1,6,2) + .85X(2,6,1) + \\
&1.1X(2,6,2) + .85X(3,6,1) + \\
&1.1X(3,6,2) + .85X(8,6,1) = 16.86
\end{aligned} \tag{92}
$$

Section 7:

$$
\begin{aligned}
&.85X(4,7,1) + 1.1X(4,7,2) + \\
&.85X(5,7,1) + 1.1X(5,7,2) + \\
&.85X(6,7,1) + 1.1X(6,7,2) + \\
&.85X(7,7,1) + .85X(8,7,1) + \\
&.85X(9,7,1) + .85X(14,7,1) + \\
&1.1X(14,7,2) + .85X(9,7,5) + \\
&.85X(1,7,1) + 1.1X(1,7,2) + \\
&.85X(2,7,1) + 1.1X(2,7,2) + \\
&.85X(3,7,1) + 1.1X(3,7,2) + \\
&.85X(10,7,1) + .85X(11,7,1) + \\
&.85X(12,7,1) + .85X(13,7,1) + \\
&1.1X(13,7,2) = 424.36
\end{aligned} \tag{93}
$$

Section 8:

$$
\begin{aligned}
&.85X(4,8,1) + 1.1X(4,8,2) + \\
&.85X(5,8,1) + 1.1X(5,8,2) + \\
&.85X(6,8,1) + 1.1X(6,8,2) + \\
&.85X(7,8,1) + .85X(8,8,1) + \\
&.85X(9,8,1) + .85X(10,8,1) + \\
&.85X(11,8,1) + .85X(12,8,1) + \\
&.85X(14,8,1) + 1.1X(14,8,2) + \\
&.85X(9,8,5) + 1.1X(13,8,2) + \\
&1.1X(1,8,2) + .85X(2,8,1) + \\
&1.1X(2,8,2) + .85X(3,8,1) + \\
&1.1X(3,8,2) + .85X(1,8,1) = 558.35
\end{aligned} \tag{94}
$$

Section 9:

$$
\begin{aligned}
&.85X(4,9,1) + 1.1X(4,9,2) + \\
&.85X(5,9,1) + 1.1X(5,9,2) + \\
&.85X(6,9,1) + 1.1X(6,9,2) + \\
&.85X(7,9,1) + .85X(8,9,1) +
\end{aligned}
$$

$$
\begin{aligned}
&.85X(9,9,1) + .85X(10,9,1) + \\
&.85X(11,9,1) + .85X(12,9,1) + \\
&.85X(14,9,1) + 1.1X(14,9,2) + \\
&.85X(9,9,5) + 1.1X(13,9,2) + \\
&.85X(1,9,1) + 1.1X(1,9,2) + \\
&.85X(2,9,1) + 1.1X(2,9,2) + \\
&.85X(3,9,1) + 1.1X(3,9,2) = 547.68
\end{aligned}
\tag{95}
$$

Section 10:

$$
\begin{aligned}
&.85X(5,10,1) + 1.1X(5,10,2) + \\
&.85X(6,10,1) + 1.1X(6,10,2) + \\
&.85X(8,10,1) + .85X(9,10,1) + \\
&.85X(10,10,1) + .85X(11,10,1) + \\
&.85X(12,10,1) + .85X(13,10,1) + \\
&.85X(14,10,1) + 1.1X(14,10,2) + \\
&.85X(9,10,5) + 1.1X(13,10,2) + \\
&.85X(2,10,1) + 1.1X(2,10,2) + \\
&.85X(3,10,1) + 1.1X(3,10,2) + \\
&.85X(4,10,1) + 1.1X(4,10,2) + \\
&.85X(7,10,1) = 224.63
\end{aligned}
\tag{96}
$$

Section 11:

$$
\begin{aligned}
&.85X(5,11,1) + 1.1X(5,11,2) + \\
&.85X(6,11,1) + 1.1X(6,11,2) + \\
&.85X(9,11,1) + .85X(10,11,1) + \\
&.85X(11,11,1) + .85X(12,11,1) + \\
&.85X(13,11,1) + .85X(14,11,1) + \\
&1.1X(14,11,2) + .85X(9,11,5) + \\
&1.1X(13,11,2) + .85X(3,11,1) + \\
&1.1X(3,11,2) + .85X(4,11,1) + \\
&1.1X(4,11,2) + .85X(7,11,1) + \\
&.85X(8,11,1) = 249.03
\end{aligned}
\tag{97}
$$

Section 12:

$$
\begin{aligned}
&.85X(6,12,1) + 1.1X(6,12,2) + \\
&.85X(10,12,1) + .85X(11,12,1) + \\
&.85X(12,12,1) + .85X(13,12,1) + \\
&.85X(14,12,1) + 1.1X(14,12,2) + \\
&.85X(9,12,5) + 1.1X(13,12,2) + \\
&.85X(4,12,1) + 1.1X(4,12,2) + \\
&.85X(5,12,1) + 1.1X(5,12,2) + \\
&.85X(8,12,1) + .85X(9,12,1) = 270.51
\end{aligned}
\tag{98}
$$

Section 13:

$$
\begin{aligned}
&.85X(6,13,1) + 1.1X(6,13,2) + \\
&.85X(10,13,1) + .85X(11,13,1) + \\
&.85X(12,13,1) + .85X(13,13,1) + \\
&.85X(14,13,1) + 1.1X(14,13,2) +
\end{aligned}
$$

$$
\begin{aligned}
&.85X(9,13,5) + 1.1X(13,13,2) + \\
&.85X(5,13,1) + 1.1X(5,13,2) + \\
&.85X(8,13,1) + .85X(9,13,1) = 138.12 \qquad (99)
\end{aligned}
$$

Section 14:

$$
\begin{aligned}
&.85X(11,14,1) + .85X(12,14,1) + \\
&.85X(13,14,1) + .85X(14,14,1) + \\
&1.1X(14,14,2) + .85X(9,14,5) + \\
&1.1X(13,14,2) = 47.19 \qquad (100)
\end{aligned}
$$

Assuming that the contractor does not intend to use borrow (since cut exceeds fill quantity), the following constraint prevents the borrow variables from entering the solution:

$$
\begin{aligned}
&X(9,7,5) + X(9,8,5) + X(9,9,5) + X(9,10,5) \qquad (101) \\
&X(9,11,5) + X(9,12,5) + X(9,13,5) + X(9,14,5) \leq 0.0001
\end{aligned}
$$

Simulation of LP Output Coefficients

The coefficients of the variables appearing in Table 7-14 were replicated for 100 cycles with a confidence factor of 67 percent. The choice of 100 cycles was arbitrary but based on the objective of reducing computer cost and the results of the example problem which showed little change in coefficient ranges as the cycles were increased from 100 to 500. Confidence factors of 50 and 85 percent were also used during simulation runs. As the confidence factor was increased, two definite trends were noted. First of all, the total unit cost decreased from \$1.93/BCY for a confidence factor of 50 to \$1.88/BCY for a confidence factor of 85. The second opposing trend was the increased incompatibility of simulation and LP coefficient ranges as the confidence factor was increased.

TABLE 7-14

LP Output

Objective Function Value

$5667992.00

Variable	Value	Reduced Cost
X113	211.51	0.00
X114	11.36	0.00
X221	13.11	0.00
X231	43.87	0.00
X441	40.64	0.00
X481	186.03	0.00
X482	151.01	0.00
X551	56.82	0.00
X561	19.84	0.00
X571	264.60	0.00
X572	181.32	0.00
X582	111.59	0.00
X681	29.98	0.00
X691	203.88	0.00
X692	184.69	0.00
X781	1.90	0.00
X8101	11.23	0.00
X9111	9.70	0.00
X10111	15.02	0.00
X11111	45.54	0.00
X12111	43.52	0.00
X13121	60.02	0.00
X14112	131.13	0.00
X14121	107.37	0.00
X14122	77.98	0.00
X14131	162.49	0.00
X14141	55.51	0.00
X13122	38.59	0.00
X192	155.66	0.00
X281	73.49	0.00
X2102	91.13	0.00
X381	25.64	0.00
X3101	58.78	0.00
X3102	58.98	0.00
X4112	7.34	0.00
Total 35		

AD-A145 563 OPTIMIZING EARTHWORK ESTIMATING FOR HIGHWAY CONSTRUCTION(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH F T UHLIK AUG 84 AFIT/CI/NR-84-58T

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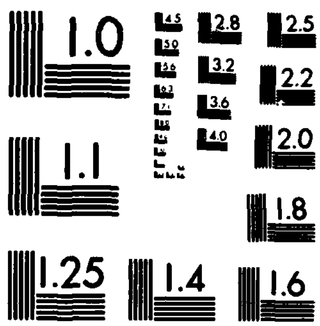

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Interpretation of Output

Table 7-15 presents a comparison of the coefficient ranges obtained from the simulation (confidence factor = 67 percent) and the LP sensitivity analysis. Also, the quantity of material and the fractional compatibility of the ranges for each variable are shown on the table. Fractional compatibility is a parameter defined as that fraction of the simulation range which falls within the LP sensistivity range for a specific variable. Since there are 100 values for each coefficient, the central limit theorem applies and the coefficients follow a normal distribution. Appendix D shows how the data obtained from the simulation and standard normal tables were used to calculate the fractional compatibility. This parameter was used to compute a Reliability Index as shown at the end of Table 7-15. The Reliability Index is a weighted average of the product of the quantity and fractional compatibility of each solution variable. The computed Reliability Index of 0.69 for this problem means that, on average, in 69 out of 100 cases the proposed system will provide a total unit cost distribution that accurately reflects the optimum cut/fill variables selected by the LP solution. The remaining 31 cases will contain some incompatibility indicating a sub-optimal solution.

Table 7-16 shows the rock quantity sensitivity analysis. With the exception of section 1, the LP ranges

TABLE 7-15

Comparison of Coefficient Ranges

Variable	Quantity	Coefficient Ranges: Simulation / LP Sensitivity	Fractional Compatibility
X(113)	211.51	622 - 792 / 0 - 924	1.00
X(114)	11.36	863 - 985 / 708 - 1107	1.00
X(221)	13.11	885 - 1005 / 0 - 1124	1.00
X(231)	43.88	1037 - 1176 / 0 - 1258	1.00
X(441)	40.64	884 - 1011 / 0 - 1095	1.00
X(481)	186.03	2182 - 2478 / 2194 - 2366	0.79
X(482)	151.01	2715 - 3016 / 2785 - 2891	0.58
X(551)	56.82	889 - 1032 / 0 - 978	0.90
X(561)	19.84	1174 - 1335 / 0 - 1307	0.97
X(571)	264.60	1604 - 1794 / 1692 - 1768	0.50
X(572)	181.32	2044 - 2281 / 2096 - 2194	0.63

TABLE 7-15 (Continued)

Comparison of Coefficient Ranges

Variable	Quantity	Coefficient Ranges: Simulation / LP Sensitivity	Fractional Compatibility
X(582)	11.59	2530 - 2831 / 2658 - 2756	0.46
X(681)	29.98	1169 - 1307 / 1224 - 1281	0.61
X(691)	203.88	1391 - 1552 / 1462 - 1519	0.47
X(692)	184.69	1789 - 2015 / 0 - 1919	0.90
X(781)	1.90	1038 - 1181 / 0 - 1105	0.68
X(8101)	11.23	1343 - 1758 / 0 - 1493	0.75
X(9111)	9.70	1472 - 1672 / 0 - 1580	0.75
X(10111)	15.02	1052 - 1358 / 0 - 1372	1.00
X(11111)	45.54	903 - 1081 / 0 - 1338	1.00
X(12111)	43.52	1070 - 1372 / 0 - 1185	0.68
X(13121)	60.02	1025 - 1179 / 424 - 1179	1.00

TABLE 7-15 (Continued)

Comparison of Coefficient Ranges

Variable	Quantity	Coefficient Ranges: Simulation / LP Sensitivity	Fractional Compatibility
X(14112)	131.13	1890 - 2093 / 1960 - 2031	0.55
X(14121)	107.38	1238 - 1406 / 1291 - 1346	0.54
X(14122)	77.98	1600 - 1789 / 1657 - 1727	0.57
X(14131)	162.49	988 - 1136 / 0 - 1085	0.94
X(14141)	55.52	868 - 998 / 0 - 968	0.98
X(13122)	38.59	1142 - 1290 / 0 - 1499	1.00
X(192)	155.66	3457 - 4010 / 3585 - 3881	0.74
X(281)	73.49	2479 - 2793 / 2486 - 2641	0.59
X(2101)	91.13	3697 - 4140 / 0 - 4023	0.90
X(381)	25.64	2154 - 2483 / 2333 - 2366	0.32

TABLE 7-15 (Continued)

Comparison of Coefficient Ranges

Variable	Quantity	Coefficient Ranges: Simulation / LP Sensitivity	Fractional Compatibility
X(3101)	58.78	2763 - 3117 / 2915 - 2949	0.16
X(3102)	58.98	3388 - 3808 / 0 - 3666	0.94
X(4112)	7.34	3932 - 4484 / 4200 - 4306	0.37

Calculation of Reliability Index (RI)

$$RI = \frac{(\text{Quantity x fractional compatibility})}{\text{Quantity}}$$

$$= \frac{\begin{array}{l} 211.51(1) + 11.36(1) + 13.11(1) + \\ 43.88(1) + 40.64(1) + 186.03(.79) + \\ 151.01(.58) + 56.82(.9) + 19.84(.97) + \\ 264.6(.5) + 181.32(.63) + 111.59(.46) + \\ 29.98(.61) + 203.88(.47) + 184.69(.47) + \\ 1.9(.68) + 11.23(.75) + 9.7(.75) + \\ 15.02(1) + 45.54(1) + 43.52(.68) + \\ 60.02(1) + 131.13(.55) + 107.38(.54) + \\ 77.98(.57) + 162.49(.94) + 55.52(.98) + \\ 38.59(1) + 155.66(.74) + 73.49(.59) + \\ 91.13(.9) + 25.64(.32) + 58.78(.16) + \\ 58.989(.94) + 7.34(.37) \end{array}}{2941.27}$$

RI = .69

TABLE 7-16

Rock Quantity Sensitivity

Section	Mean (000 BCY)	LP Range (000 BCY)	Percent Confidence Interval
1	151.41	155.66 - 378.53	50
2	81.99	71.32 - 136.55	86
3	53.06	8.98 - 104.40	99 +
4	142.46	108.35 - 260.28	99 +
5	253.67	242.91 - 394.84	67
6	167.42	134.69 - 388.57	99 +
13	34.51	0.00 - 70.90	99 +
14	187.07	159.11 - 241.42	98

all bracket the estimated mean quantities of rock. The confidence intervals range from 50 to over 99 percent and suggest that the LP solution is rather insensitive with regard to rock quantity.

A review of the complete LP output (Appendix D) shows that there is at least one alternative solution since the reduced cost of variables X(2,10,1) and X(7,10,1) is zero and these variables are not in the current solution. The alternative solution would probably consist of the substitution of the above variables for X(3,10,1) and X(8,10,1). No further evaluation was conducted on alternative solutions.

Table 7-17 shows the percentiles of the total unit cost computed by the proposed system. Note that, in addition to the nine standard intervals, the costs corresponding to the 68th, 95th, and 99th percentiles were also requested. The cumulative probability plot of the total unit cost will be presented in a later section that compares the various estimates prepared for the case study problem.

SEMCAP Estimate

The case study problem was also estimated on SEMCAP (Systematic Earthmoving Cost Analysis Program -- a system initially devised by former civil engineering graduate student Fran Love) using the DRILLBLAST, RIPPING, FELOADER, TRUCK, LOADHAUL, SCRAPER, COMPACT, and PROFILEPLOT Modules.

TABLE 7-17

Percentiles of Total Unit Cost

Percent	Unit Cost ($/BCY)	No. of Obs.
10.00	1.84	10
20.00	1.86	20
30.00	1.87	30
40.00	1.88	40
50.00	1.90	50
60.00	1.91	60
70.00	1.93	70
80.00	1.95	80
90.00	1.98	90

The lower quartile is: 1.87

The upper quartile is: 1.94

68.00	1.92	68
95.00	2.00	95
99.00	2.03	99

Table 7-18 summarizes the SEMCAP estimate. The actual input instructions and input data are included in Appendix E. Figures 7-3 and 7-4 are the profile plot and haul-mass diagram prepared by the SEMCAP function PROFILEPLOT.

Estimate From Estimating Guides

This section summarizes the earthwork estimate prepared using the RICHARDSON SYSTEM for a scraper fleet and the Dodge Guide for a loader-truck fleet and rock blasting. The quantities are the same as those used for the previous estimates and the average haul distance is assumed to be 3000 feet. The scraper fleet will be used to remove the 1.76 million BCY of earth (60% of total) and the loader-truck fleet will remove the 1.18 million BCY of rock (40% of total).

Scraper Fleet (RICHARDSON SYSTEM [1981])

Table 7-19 summarizes the fleet costs. The total quantity of excavation is 2,941,272 BCY x .60 = 1,764,763 BCY. The following steps are then used to calculate the unit cost.

1. 1,764,763 BCY ÷ 867 BCY/hr. (average production for a 3000-foot haul) = 2035.5 hours
2. 2035.5 hours rounds up to 2036 hours.
3. 2036 hours at $1,410/hr. = $2,870,760
4. Moving equipment to site:

   10 loads x 2 hrs./load x $264/hr. = 5,280
5. Final grading based on $.03/square

TABLE 7-18

Summary of SEMCAP Estimate

Operation	Quantity (BCY)	Unit Cost ($/BCY)	Total Operation Cost ($)
Ripping	600,000	$0.13	$78,000
Scrapers	1,764,763	$1.29	$2,276,545
Loader-Truck	1,176,509	$0.90	$1,058,858
Drilling/Blasting	1,176,509	$0.71	$ 835,322
Compaction	2,745,266	$0.20	$ 549,053
		Total	$4,797,778

Total Unit Cost = Total Operation Cost ÷ Total Volume

= 4,797,778 ÷ 2,941,272

= $1.63/BCY

NOTES: 1. An efficiency factor of .85 was used for this estimate.

2. Average cycle time components were selected from the Caterpillar Handbook and used for this estimate.

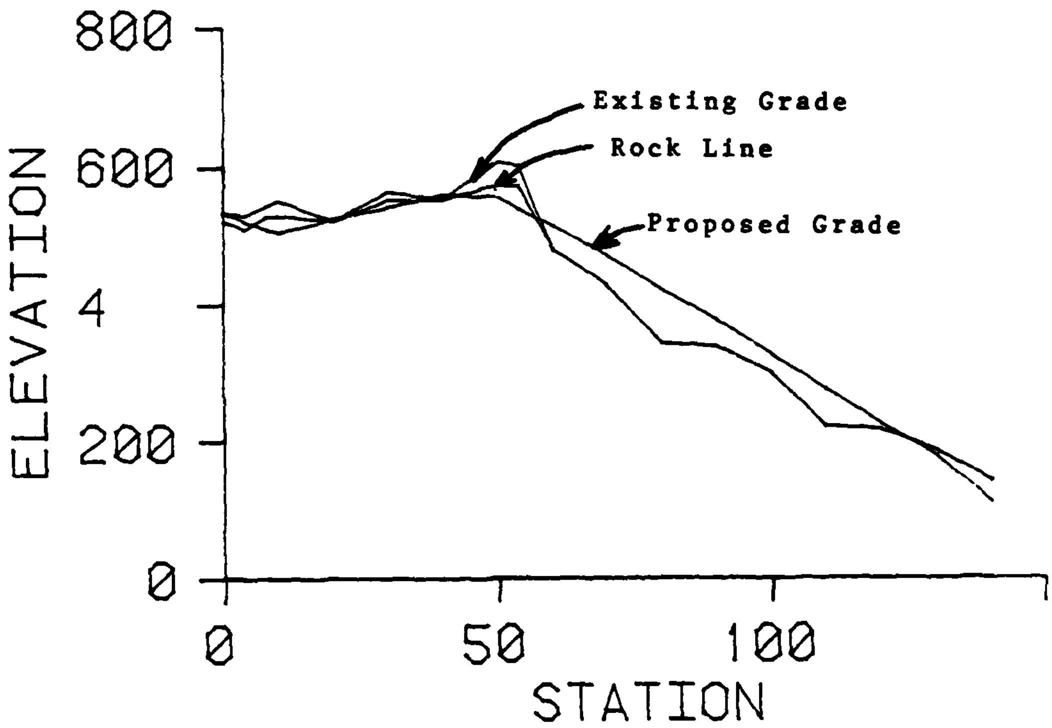

FIGURE 7-3 SEMCAP Profile Plot

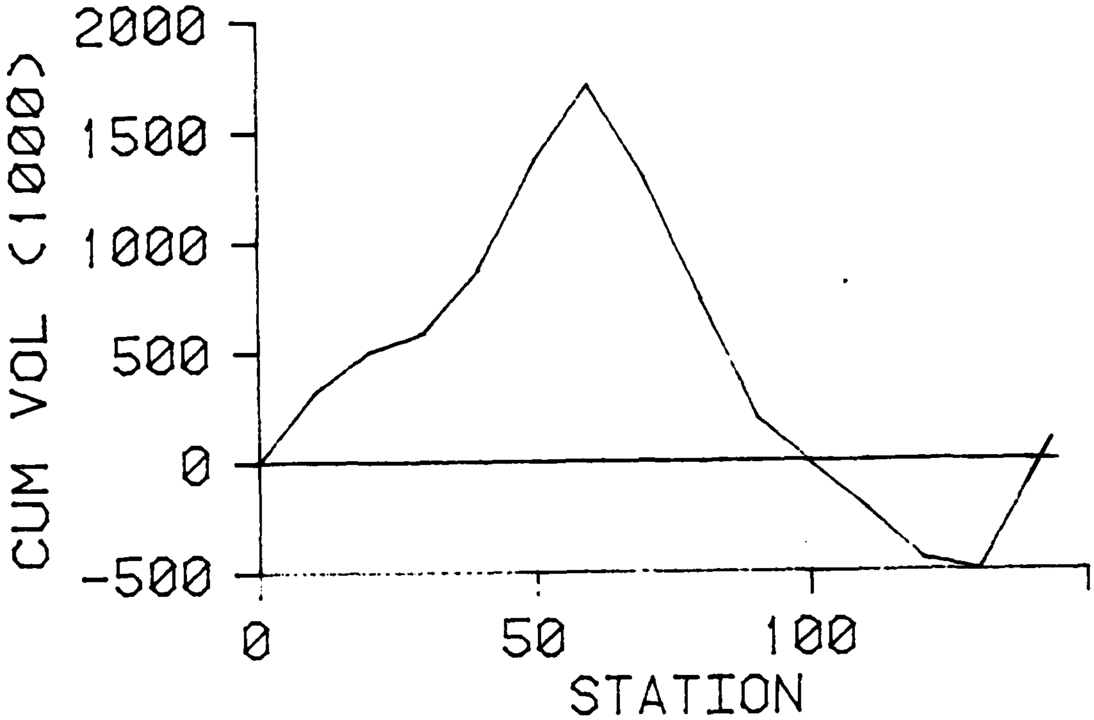

FIGURE 7-4 SEMCAP Haul-Mass Plot

TABLE 7-19

RICHARDSON SYSTEM Scraper Fleet Costs

Equipment	Rental ($/Hr.)	Labor ($/Hr.)
D-9H Pushcat	$144.00	$16.82
D-8K Dozer-Ripper	115.00	16.82
631D Scraper (5 each)	748.00	84.10
Roller-Dozer	121.00	16.82
Grader	53.00	16.82
Water Truck	23.00	13.27
Foreman w/Pickup	6.60	17.32
Grade Checker	-----	17.32
Sub-Total	$1,210.60	$199.29

Total $1,410.00/Hr.

foot of area:

14000 ft. x 60 ft. x .60 x \$.03/SF = 15,120

Total	\$2,891,160

6. Unit Cost:

\$2,891,160 ÷ 1,764,763 BCY = \$1.64/BCY

7. Correction factor for inflation:

1980 to 1981 assume 15% increase

1980 unit cost = \$1.64/BCY ÷ 1.15 = \$1.43/BCY

Loader-Truck Fleet (Dodge [1982])

The total quantity moved by this fleet is 2,941,272 BCY x .40 = 1,176,509 BCY. Assuming the material is primarily broken rock and a 10 BCY capacity loader, the daily output is 5500 BCY/day at a unit cost of \$0.33 per BCY. Four off-road trucks are required at a unit cost of \$1.01 per BCY for a 3000-foot haul. The loader-truck fleet cost is then \$0.33 plus \$1.01 or \$1.34 per BCY.

The drilling and blasting costs are assumed to average \$.95 per BCY of rock. Compaction adds another \$.35 per BCY.

These costs, since they are in terms of 1982 dollars, must be adjusted for inflation to reflect 1980 costs. Inflation rates of 15% (1980 to 1981) and 10% (1981 to 1982) are applied to the costs as follows:

Loader-truck:	\$1.34/BCY ÷ (1.15 x 1.10)	= \$1.06/BCY
Drilling and Blasting:	\$0.95 ÷ (1.15 x 1.10)	= \$0.75/BCY
Compaction:	\$0.35 ÷ (1.15 x 1.10)	= \$0.28/BCY

Table 7-20 summarizes the unit costs for this estimate. Note that only the quantity of each type of material and the average haul distance were required in order to complete this estimate.

Comparison of Estimates

This section compares the five estimates applied to the case study and presented in the previous sections with regard to: (1) unit cost versus actual reported unit cost, (2) output information available to management, (3) type of input information required, (4) computer support required, and (5) length of time required to prepare estimate.

Figure 7-5 shows the total unit costs of the five estimates considered in this section. As one can see, all but the proposed system, indicates a single value ranging from $1.54/BCY to $1.83/BCY for the total unit cost. The proposed system displays a cumulative probability curve ranging from $1.80/BCY to $2.05/BCY.

At this point, it should be emphasized that the five estimates re-constructed in this chapter used the most appropriate data available and no attempt was made to "bias" the estimates in any direction. The PennDOT and contractor estimates were copied (after deleting indirect costs) from the actual estimate sheets. The SEMCAP and Estimating Guide estimates were prepared according to the guidelines of each system and the contractor's costs/productivity values were used as applicable. The proposed system used both

TABLE 7-20

Estimating Guide Total Unit Cost

Operation	Quantity (BCY)	Unit Cost ($/BCY)	Total Cost ($)
Scraper Fleet	1,764,763	1.43	2,523,611
Loader-Truck Fleet	1,176,509	1.06	1,247,100
Drilling and Blasting	1,176,509	0.75	882,382
Compaction	2,608,002	0.28	730,241
			5,383,334

Total Unit Cost = $5,383,334 ÷ 2,941,272 BCY

= $1.83/BCY

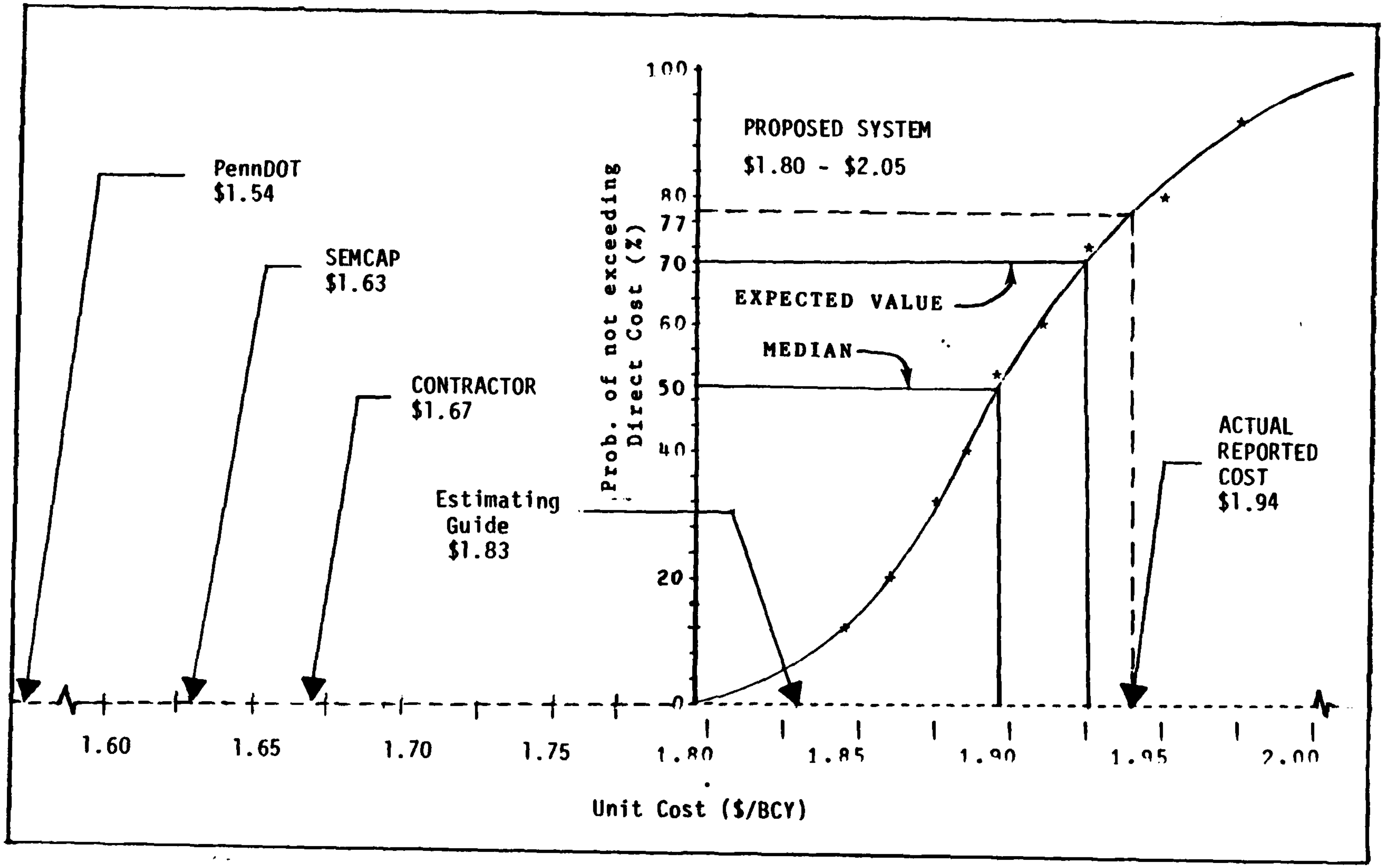

FIGURE 7-5 Comparison of Unit Cost Estimates

contractor costs and productivity values to generate its estimate. Also, the proposed system used the input and insight of the estimators who actually estimated the project several years ago. Nevertheless, efforts were made to insure that the same amount of information (i.e., that known at the pre-bid stage) was used in preparing each of the five estimates.

It is important to note that the five estimates are compared to a "reported" rather than "actual" cost. The "actual" or true cost of a project is seldom, if ever, known. The primary reason for this situation deals, to a large extent, with project cost accounting practices but is also influenced by equipment maintenance, depreciation and the indirect costs allocated to the project. The reported direct cost of \$1.94/BCY (corresponding to the 77th percentile), as shown in Figure 7-5, was obtained from the contractor's "Summary Cost Breakdown" computer printout. It is interesting to note that the total (direct + indirect) reported unit cost for the project was \$2.33/BCY. Based on a bid price of \$2.28/BCY and a quantity of over 2.9 million BCY, this represents a loss of almost \$150,000! As can be seen in Figure 7-5, the proposed system is the only one which provides values which are close to the actual "reported cost".

Figure 7-5 also shows the expected and median (corresponding to the 50th percentile) values of the proposed system's estimate. The expected value of \$1.93/BCY (corresponding to the 70th percentile) was obtained by dividing the total earthmoving cost (see Table 7-8) as follows:

$$\text{Expected Value} = \frac{\$5,667,992}{2,941,272 \text{ BCY}} = \$1.93/\text{BCY} \qquad (102)$$

It is interesting to note what affect, if any, a bid based on the expected value would have had on the contract award. If one considers the same markup of \$.61/BCY used for the actual bid and adds it to the expected unit cost of \$1.93/BCY, a bid of \$2.54/BCY would result. Based on the actual bids, the contractor's bid for the entire project would have been \$582,000 higher and he would have been the second rather than the lowest bidder and would not have been awarded the contract! Thus, although the proposed system provides accurate information related to direct costs, other factors including indirect costs, contingency factors, profit markup, and bidding strategy must also be evaluated when formulating a successful unit-cost bid.

For the purposes of comparison, the case study LP problem was solved assuming that borrow was available within section 9 (This area was selected since it is the center of fill on the haul-mass diagram). Assuming that borrow land could have been bought for \$2,000 per acre (an average figure quoted by the contractor), the total project cost (including purchase of borrow acreage) using borrow from section 9 would have been reduced by more than \$250,000. The reason for this decrease stems directly from the savings in haul costs and serves to emphasize the importance of this single element on the total cost of earthwork.

As far as information available to management, only the proposed system estimate contains both quantitative and qualitative information. It depicts the probability (from 0 to 100) of not exceeding the total unit cost (plotted on the ordinate) versus the total unit cost (plotted on the abscissa). In addition, percentiles are available to match the unit cost to a specified percentage or risk. The Reliability Index provides an indication of the quality of the estimate. While the contractor's estimate may include a range (based upon independent estimates or productivities), it does not contain any probabilistic information nor does it give any quantitative clue as to its quality (based on input values). The other three estimates fare even worse in this regard because, by their very nature, they rely on very general parameters and can cause significant distortion when applied to a single contractor who might use different equipment, fleets, and techniques from those assumed.

The type of input information required varies from the detailed (SEMCAP) requiring bucket capacities and times of cycle time components, to the very general (Estimating Guides) that require only the total quantity, type of material, and average haul length. The earthwork contractor usually has historical data pertaining to costs and productivities that represent the most valuable source of information available. With accurate data, the earthwork contractor can devote his time to determining the quantity of rock and the optimum cut/fill distribution since he can estimate his unit costs (based on historical productivity) for excavation and compaction with a higher degree of confidence. The proposed system requires cost data that is separated into the elements of excavation (including loading), hauling (per section), and compaction (including unloading). While many contractors do not account for their costs according to this activity breakdown, it was a rather simple matter to obtain them from the cost report of the contractor who completed the case study project.

Computer support is not required (usually) for the PennDOT, contractor, and estimating guide estimates. SEMCAP requires at least a large micro-computer, with APL adaptability, for its use. The proposed system has the same requirement as SEMCAP for APL and, in addition, requires a LP software package. A relatively small (perhaps less than 50 variables) problem could be handled on a micro-computer but the storage requirements for matrices and LP formulation indicate that at least a mini-computer would be needed for a problem similar to the case study.

The time required to prepare each of the estimates, though not a major academic consideration, is significant from a practical viewpoint. Without giving a specific number of hours, it is reasonable to rank order the estimates in ascending order according to the time necessary for their completion (i.e., first mentioned took the least time) as follows:

1. Estimating Guide
2. SEMCAP
3. PennDOT
4. Proposed System
5. Contractor.

(Note that only estimates 1, 2, and 4 above were completely prepared by the writer. The ranking of estimates 3 and 5 was based on consultation with the respective parties).

The contractor estimated that he spent approximately 175 man-hours (including test drilling) preparing the estimate for the case study project. Based on the limited experience with the proposed system, it is felt that a similar project could be estimated in approximately 120 man-hours (including test drilling) due to computer support in handling calculations.

Contractor Feedback

A part of the research effort was directed towards obtaining contractor feedback by maintaining communication with the case study contractor, briefing him on the results of the research, and soliciting and evaluating his comments. This section summarizes that portion of the research dealing with contractor feedback.

Communication

The initial contact with the case study contractor was made in April 1983. Since that time, communication has existed on a continuing basis. The contractor was visited on eight separate occasions for the purposes of collecting data, verifying transformed data, and explaining results/receiving feedback. Estimating, engineering, and executive personnel were interviewed. Despite a busy schedule, the contractor was always willing to set aside time for meetings related to the case study.

Contractor Verification

An important objective of one of the final contractor meetings was to verify that the cost and production data, supplied by the contractor, had been correctly incorporated into the proposed system. By jointly reviewing how the data was transformed from contractor records to proposed system input, verification of the case study data was achieved.

Contractor Comments

The final meeting with the contractor was devoted to briefing him on the proposed system and obtaining his comments. The general concensus of the contractor personnel was that the proposed system "appeared to be an effective estimating tool." They cited keener competition and fewer projects as reasons why an improvement in estimating methods was needed. Although the contractor personnel understood the major models included in the proposed system, they were not familiar with LP techniques and, for this reason, would have difficulty in implementing the proposed system.

Some of the contractor comments were enlightening due to the different perspective from which they viewed the system. They felt, for example, that their estimating methods, while not related to any specific mathematical models or computer techniques, essentially duplicated the results obtained by the proposed system (Note that the results of the case study did not support this opinion of the contractor). Another interesting comment expressed the concern that a new estimating system such as the one proposed, could "account for too much of the actual cost" and the resulting project bid might be too high to enable them to get the project (i.e., they might be 2nd or 3rd rather than low bidder). While such a comment is difficult to understand from a logical viewpoint, it does indicate that intuition and uncertainty have become so ingrained within the industry that some contractors feel uncomfortable about the prospect of using more accurate estimating data.

The contractor personnel recommended that the proposed system be applied to additional projects in order to more fully validate its effectiveness. They also brought out the fact that unsuitable material is another category (along with earth and rock) that should be incorporated into the system because it can significantly affect the cut/fill distribution. Finally, the contractor mentioned that he would like to see the proposed system expanded so that the optimum fleet configuration (in addition to the optimum material distribution) could be determined without the need for re-entering new data for each fleet.

Summary

This chapter presented a case study project and discussed five independent methods of estimating the earthwork. First, the PennDOT estimate was described followed by the successful contractor's estimate. Next, the proposed system was explained in detail as it was applied to the case study. The estimates from SEMCAP and estimating guides were presented next and all five estimates were compared according to a number of factors. Finally, contractor feedback related to the case study was summarized.

The next and final chapter presents the conclusions, findings, and recommendations. It seeks to both filter out the significant elements of this thesis and to propose future actions related to the expansion of issues only peripherally addressed in this study.

CHAPTER EIGHT

CONCLUSIONS, FINDINGS AND RECOMMENDATIONS

The major findings of this research effort, as well as pertinent recommendations, are presented in this chapter. The major conclusions will be presented first followed by other findings and the recommendations.

Conclusions

The major conclusions relate directly to the objectives outlined at the beginning of this thesis and are based on the limited experience of applying the proposed system to a case study problem.

1. The feasibility of applying probabilistic estimating in conjunction with linear programming to an earthmoving project has been demonstrated.
2. The uncertainty involved with estimating the quantity of rock in cut areas can be addressed by chance-constrained programming -- a technique that transforms stochastic constraints into deterministic ones.
3. The variability in production rates for excavation, haul, and compaction can be accounted for thru the use of 3-value, PERT-type estimates.
4. An LP formulation, incorporating chance

constraints for the rock quantities and expected values for the cost coefficients, will, when correctly applied, provide the optimum cut/fill distribution.

5. The proposed system, utilizing simulation and the LP output, produces a plot of the cumulative probability of not exceeding the unit cost versus unit cost. This plot provides additional information not present in the traditional estimates.

Findings

The findings focus on general areas related to earthwork estimating:

1. Estimating, in many respects, is still an "art" rather than a defined operation. The numerous uncertainties pertaining to construction projects, compounded by the forecasting aspects of an estimate and the competitive nature of the industry create a situation that defies quantitative analysis. Probabilistic estimating, though only in its infancy, represents the state-of-the-art in improving estimating techniques.

2. Earthwork contractors, in preparing their estimate, do not devote enough effort to analyzing the cut/fill distribution in order to

arrive at a plan that approaches the optimum. The haul cost is a major variable in determining the total unit cost. Of the five estimating techniques considered, only the proposed system requires the estimator to individually consider each haul route associated with the project.

3. The ability afforded by the proposed system to increase the level of detail of earthwork elements (i.e., variables X(1,3,1) and X(1,3,2) but not variables X(8,10,1) and X(8,10,2), for example) represents the equivalent of the "successive estimating" concept proposed by Lichtenberg (1976). It allows the estimator to meaningfully apply his experience and knowledge to those portions of the project perceived as having the greatest variance.

4. Use of the proposed system requires that the estimated costs be input in a format (i.e., excavation, haul, and compaction unit costs) that may not correspond to existing cost accounting procedures. As a result, changes will be required in existing cost accounting systems for those contractors desiring to use the proposed system so that the historical cost data can be stored in the proper format.

5. The user of the proposed system must have a basic understanding of linear programming in

order to correctly formulate the problem and evaluate the output and sensitivity analysis.

6. The use of the APL language for the proposed system simplified the programming for both the input and simulation portions of the system and allowed a "user friendly" environment to be incorporated within the system. As a result, even personnel inexperienced with computer programs can effectively make use of the proposed system.

Recommendations

The recommendations offered in this section are divided into two groups -- the first group applies to the academic community and the second to earthwork contractors. The first set of recommendations include the following:

1. Since the proposed system was only applied to one actual project, additional applications are recommended to validate its effectiveness.
2. A natural extension of the proposed system would be one that incorporates indirect costs and bidding strategy.
3. A further extension of the proposed system could entail the incorporation of the uncertainty associated with weather on earthwork operations.
4. Future research should seek to extend probabilistic estimating into other areas of

construction. Projects involving mass earthwork, such as dams, airports, and tunnels, are likely candidates for furture research.

The next recommendations apply to earthwork contractors since their input has been instrumental in obtaining the data required to support this thesis.

5. Contractors should consider revising their cost accounting/data collection procedures so that future earthwork projects can be estimated by using historical data that is in a format which is directly compatible with the proposed system.

6. Contractors, if they do not already possess one, should consider obtaining both an APL system interface and a LP package for either micro- or mini-computer application. The cost of such software is minimal when compared to the potential profit increases that could result from their use.

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APPENDIX A

DERIVATION OF DOUBLE TRIANGULAR EQUATIONS

This appendix derives the equations needed to perform Monte-Carlo sampling from the double triangular distribution described in Chapter Four.

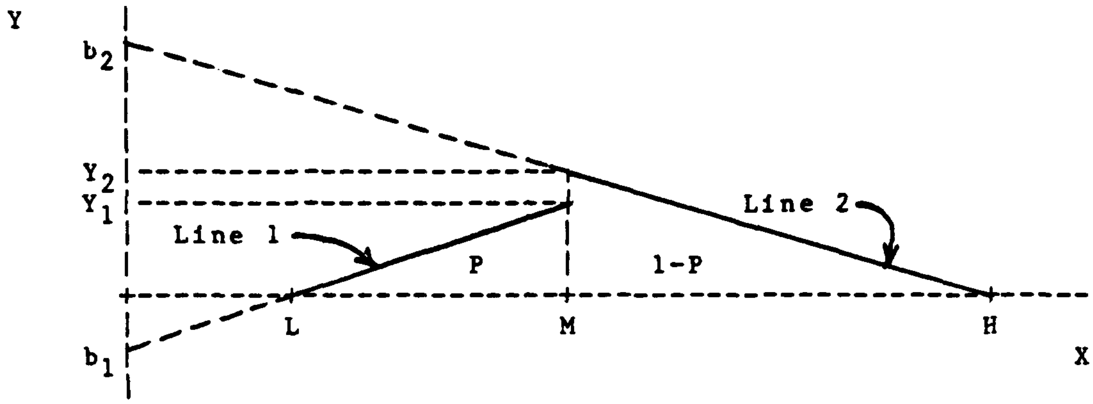


FIGURE A-1 Derivation of Double Triangular Distribution

Calculation of Equation of Line 1

The area of the left triangle equals P, therefore:

$$P = 1/2 \text{ (length) (height)} \tag{103}$$

$$P = \frac{(M-L)}{2} Y_1, \text{ and} \tag{104}$$

$$Y_1 = \frac{2P}{(M-L)} \tag{105}$$

The slope of line 1 can be calculated as:

$$\text{slope}_1 = m_1 = \frac{Y_1}{(M-L)} = \frac{2P}{(M-L)} \div (M-L) = \frac{2P}{(M-L)^2} \tag{106}$$

The general form of a straight line is $Y = mX + b$ so it only remains to calculate the value of the Y intercept, b. Using the figure above and geometry, it can be seen that

$$Y = b_1 \text{ at } X = 0 \tag{107}$$

$$b_1 = -(m_1)(L-0) \quad [\text{i.e., } (\frac{Y}{X})\ X]$$

$$= \frac{-2P}{(M-L)^2}\ L \tag{108}$$

The equation of line 1 is then

$$Y_{(\text{line 1})} = m_1 X + b_1 \tag{109}$$

substituting the value for m_1 and b_1 we have,

$$Y_{(\text{line 1})} = \frac{2P}{(M-L)^2}\ X + \frac{-2P}{(M-L)^2}\ L \tag{110}$$

and factoring the expression $\frac{2P}{(M-L)^2}$,

$$\underline{\underline{Y_{(\text{line 1})} = \frac{2P}{(M-L)^2}\ (X-L)}} \tag{111}$$

Calculation of Line 2

In a similar manner, the equation of line 2 above can be computed as follows:

The area of the right triangle equals (1-P), therefore:

$$1-P = 1/2\ (\text{length})\ (\text{height}) \tag{112}$$

$$1-P = \frac{(H-M)}{2}\ Y_2, \text{ and} \tag{113}$$

$$Y_2 = \frac{2(1-P)}{(H-M)} \tag{114}$$

The slope of line 2 can be calculated as:

$$\text{slope}_2 = m_2 = \frac{Y_2}{(H-M)} = \frac{2(1-P)}{(H-M)^2} \qquad (115)$$

Now, to get b_2 we use a similar method:

since, $$Y = m_2X + b_2 \qquad (116)$$

$$Y = b_2 \text{ at } X = 0 \qquad (117)$$

$$b_2 = (m_2)(X)$$

$$= \frac{2(1-P)}{(H-M)^2}(H-0) \qquad (118)$$

The equation of line 2 then becomes

$$Y_{(\text{line } 2)} = \frac{-2(1-P)}{(H-M)^2} X + \frac{2(1-P)}{(H-M)^2} H \qquad (119)$$

$$Y_{(\text{line } 2)} = \frac{2(1-P)}{(H-M)^2}(H-X) \qquad (120)$$

========================

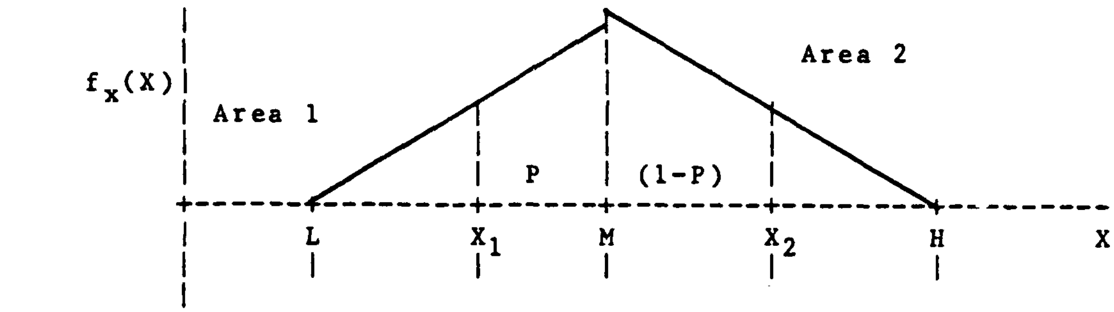
Calculation of Abscissa Quantities

Next, the areas under the curves in Figure A-2 (a) are computed to determine the equations that specify that the values to be assigned to the abscissa quantities, X, in Figure A-2 (b).

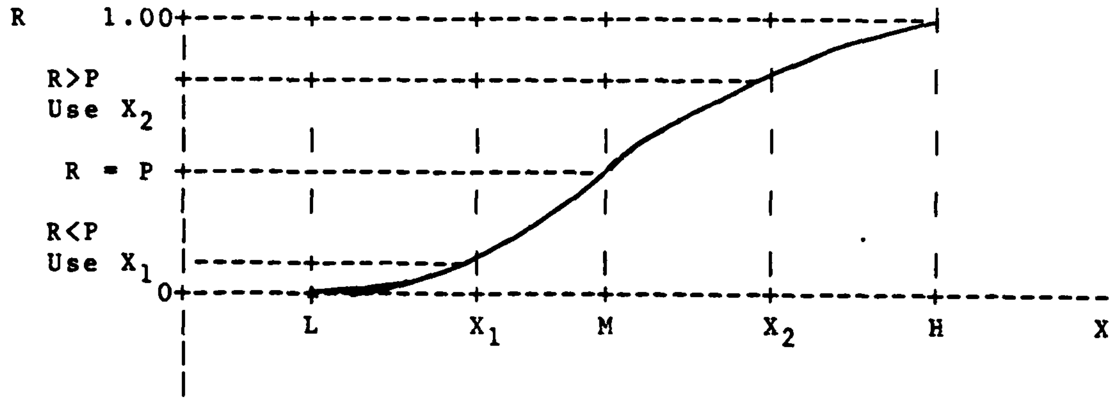
Left Triangle Calculation

For the left triangle in Figure A-2 (a), the area up to any point, X_1, is computed as:

$$\text{Area} = 1/2bh = 1/2b \times (m)(x \text{ dist.}) \qquad (121)$$



(a) Double Triangular Distribution



(b) Cumulative Probability Distribution

FIGURE A-2 Double Triangular and Cumulative Probability Distribution

$$\text{(Note: } m = \frac{Y}{X} \text{ and } m \times (X) = Y\text{)} \tag{122}$$

$$Area_1 = \frac{1}{2}(X_1-L)\ \frac{2P}{(M-L)^2}\ (X_1-L)$$

$$= \frac{(X_1-L)^2}{(M-L)^2}\,P \tag{123}$$

Note that in Figure A-2 (b) the ordinate, R, actually represents the area since it is the cumulative area under the distribution curve, Figure A-2 (a). Now, it is simply a matter of solving the above equation for X:

$$\text{Area}_1 = R = \frac{(X_1-L)^2}{(M-L)^2} P \tag{124}$$

rearranging terms,

$$(X_1-L)^2 = R/P\ (M-L)^2 \tag{125}$$

taking the square root of each side,

$$X_1-L = \quad R/P\ (M-L) \tag{126}$$

finally,

$$\underline{\underline{X_1 = L + \quad R/P\ (M-L)}} \tag{127}$$

Right Triangle Calculation

Next, the right triangle of Figure A-2 (a) is considered. The area up to any point X_2 (assuming that $X_2 > M$) can be computed as follows:

$$R = \text{Area}_2 = 1 - \quad (1/2(H-X_2))\ \frac{2(1-P)}{(H-M)^2}\ (H-X_2) \tag{128}$$

rearranging terms we have,

$$(H-X_2)^2\ (1-P) = (1-R)\ (H-M)^2, \tag{129}$$

again, rearranging terms,

$$H-X_2 = \quad \frac{(1-R)\ (H-M)^2}{(1-P)} \tag{130}$$

and, finally,

$$X_2 = H - \frac{(1-R)}{(1-P)}(H - M) \qquad (131)$$

APPENDIX B

PennDOT ESTIMATE -- BACKGROUND DATA

PennDOT Estimate

Counties: Central Pennsylvania
Route: LR XXXX

Class 1 Exc: 2,966,902 cy

Labor: $8.91 per hr.
Haul: 3,600 LF
Prog: 2,614 cy/day/unit
Days/Unit: 1135

SUMMARY

Equipment Type	Rental + Fuel & Oil	Earthwork Classification: Earth, Clay & Soft Shale 62%	Hard Shale 14%	Solid Rock 24%
1-4 cy Loader (shovel)	184.68 + 90.48	275.16	275.16	275.16
1 Bulldozer	194.64 + 90.48	285.12	285.12	285.12
3 Rollers	125.05 + 98.18	223.23	223.23	223.23
1 Grader	146.18 57.75	203.93	203.93	203.93
1-600 cf Compressor	47.32 + 32.73		80.05	80.05
Jack Hammers at 4.68			(2) 9.36	(4) 18.72
Air Hose at 1.08 per section			(4) 4.32	(8) 8.64
Total Equipment		987.44	1,081.17	1,094.85
Labor from Labor Organization Sheet		1,042.91	1,381.75	1,631.16
Total Equipment and Labor		2,030.35	2,462.92	2,726.01

Explosives

Hard Shale 2614 x .14 x .75 lbs. = 274.47
Solid Rock 2614 x .24 x 1 lb. = 627.36

901.83 Call 902 lbs.

Earth, Clay, Shale 62% at 2,030.35	=	1,258.82
Hard Shale 14% at 2,462.92	=	334.81
Solid Rock 24% at 2,726.01	=	654.24
Explosives 902 lbs. at $.25 per lb.	=	225.50
		2,483.37

2,483.37 ÷ 2,614 cy/day = $0.950

Haul 3,600 LF x 2 = 7200 LF Round Trip

at 15 mph $\frac{7200}{15 \times 5280} \times 60 =$ 5.45 min/trip

5.45	min/trip
3.00	min/load
1.00	min/unload
1.55	min/lost time
11.00	min Total

60 min ÷ 11 min/trip = 5.45 trips/hr.

$56.64 per hr. ÷ 5.45 trips per hr. =
$10.39 cost/trip ÷ 20 cy/trip $0.519

Sub Total	$1.469
20% profit, etc.	0.294
Total	$1.763

Call $1.75 cy

Shovel Progress

Earth	2,966,902 ÷ 760 x .36	=	1,405.4
Clay	2,966,902 ÷ 600 x .08	=	395.6
S. Shale	2,966,902 ÷ 690 x .18	=	774.0
H. Shale	2,966,902 ÷ 495 x .14	=	839.1
S. Rock	2,966,902 ÷ 270 x .24	=	2,637.4

6,051.5 days for 3/4 cy shovel
0.1875 for 4 cy shovel
1134.6 days per unit
Call 1,135

2,966,902 ÷ 1,135 = 2,614 cy per day per unit

Material Classification

Total Class I Excavation 2,966,902

Earth	36%	=	1,068,085 cy
Clay	8%	=	237,352 cy
S. Shale	18%	=	534,042 cy
Sub Total	62%	=	1,839,479 cy
Hard Shale	14%	=	415,366 cy
Solid Rock	24%	=	712,057 cy
Total	100%	=	2,966,902 cy

Daily Labor Organization for Power Shovel

Solid Rock

1	Foreman at 12.52	12.52
1	Shovel Op at 12.17	12.17
3	Roller Op at 9.55	28.65
1	Grader Op at 12.17	12.17
4	Jackhammer Op at 9.10	36.40
1	Bulldozer Op at 12.17	12.17
1	Compressor Op at 9.10	9.10
1	Blaster at 9.53	9.53
4	Laborers at 8.91	35.64
1	Oiler at 8.95	8.95
	Taxes and Ins. = 15%	------
		177.30

177.30 x 8 x 1.15 = 1,631.16 Total Labor

Hard Shale

1	Foreman at 12.52	12.52
1	Shovel Op at 12.17	12.17
3	Roller Op at 9.55	28.65
1	Bulldozer Op at 12.17	12.17
1	Grader Op at 12.17	12.17
2	Jackhammer Op at 9.10	18.20
1	Compressor Op at 9.10	9.10
1	Blaster at 9.53	9.53
1	Oiler at 8.95	8.95
3	Laborers at 8.91	26.73
	Taxes and Ins. = 15%	------
		150.19

150.19 x 8 x 1.15 = 1,381.75 Total Labor

Earth

1	Foreman at 12.52	12.52
1	Shovel Op at 12.17	12.17
3	Roller Op at 9.55	28.65
1	Dozer Op at 12.17	12.17
1	Grader Op at 12.17	12.17
1	Oiler at 8.95	8.95
3	Laborers at 8.91	26.73
	Taxes and Ins. = 15%	------
		113.36

113.36 x 8 x 1.15 = 1,042.91 Total Labor

Explosives

Taken from Sub

Avg. Price $.25 per lb. discounting pre-split quote.

Equipment Rates for Class I Excavation

Used 28th Edition of Rental Rates by
Associated Equipment Distributors

Ref.[1]

Shovel 4 cy
Based on Caterpillar 4 cy capacity 325 hp. (pg. 48)
4063 - 22 = 184.68 + (235 x .7 x 0.55)
Fuel at $.55 per gal Oil at $.55 per qt

Bulldozer
Based on Caterpillar D8H 235 hp. (pg. 44)
4282 - 22 = 194.64
235 x .7 x .55 = 90.48

Rollers based on 3 wheel 10 ton gasoline (pg. 12)
3 required
917 - 22 x 3 = 125.05
85 hp.
3 (85 x .7 x .55) = 98.18

Grader based on Caterpillar 145 (pg. 56)
3216 - 22 = 146.18
150 x .7 x .55 = 57.75

Air Compressor 600 cf
1041 - 22 = 47.32
85 hp.
85 x .7 x .55 = 32.73

Jackhammers Rock Drills (pg. 4)
65 lbs and up
103 - 22 = 4.68

Hose 1"
50% 23.75 - 22 = 1.08

Haul Estimate

Hauling Cost 30 to 35 cy truck off road rear dump (pg. 49)
6193 - 22 = 281.50
220 hp.
220 x .7 x .55 = 84.70

Labor from wage rates
8.47 x 1.15 x 8 x 1.15 = 86.88

453.08 - 8 = 56.64 per hr.

NOTES: 1. Page references refer to the 28th Edition of Rental Rates.

TABLE B-1

Haul-Mass Data

Sect.	Station Approx. 1000ft.	Excav. BCY	Embank. CCY	Excav. CCY	Excess (-)	Excess (+)	Mass Curve Ordinate	Shrinkage Factor
1	569+30-581+11.93	378,527	0	363,386	-------	363,386	363,386	.96
2	9+66.28-20+00	221,603	11,137	201,659	-------	190,522	553,908	.91
3	20+00-30+00	143,402	37,289	126,194	-------	88,905	642,813	.88
4	30+00-40+00	367,983	15,002	327,505	-------	312,503	955,316	.89
5	40+00-50+00	667,113	67,636	640,428	-------	572,792	1,528,108	.96
6	50+00-60+00	397,370	11,886	377,502	-------	365,616	1,893,724	.95
7	60+00-70+00	0	422,263	-------	422,263	-------	1,471,461	---
8	70+00-80+00	788	553,067	670	552,397	-------	919,064	.85
9	80+00-90+00	6,720	547,192	5,712	541,480	-------	377,584	.85
10	90+00-100+00	5,939	224,633	5,048	219,585	-------	157,999	.85
11	100+00-110+00	9,905	246,290	8,419	237,871	-------	-79,872	.85
12	110+00-120+00	6,439	268,948	5,473	263,475	-------	-343,347	.85
13	120+00-130+00	45,493	126,497	39,124	87,373	-------	-430,720	.86
14	130+00-143+85	549,937	41,226	489,444	-------	448,218	17,498	.89
	Total	2,801,219	2,573,066	2,590,564	2,324,444	2,341,942		
			17,498		17,498			

TABLE B-2

Elevations
(Eastbound Profiles Used)
LR XXXX Only

	Existing	Final	Final -Cut	Final +Fill
569+30	2328	2293	35	--
574+90	2331	2299	32	--
581(9+66)	2353	2305	48	--
15+08	2335	2313	22	--
20+00	2320	2323	--	3
25+00	2340	2332	8	--
30+00	2365	2342	23	--
35+00	2367	2351	16	--
40+00	2352	2360	--	8
45+00	2372	2362	10	--
50+00	2405	2354	51	--
55+00	2386	2337	49	--
60+00	2277	2314	--	37
65+00	2216	2291	--	75
70+00	2224	2270	--	46
75+00	2182	2245	--	63
80+00	2139	2221	--	82
85+00	2137	2198	--	61
90+00	2136	2175	--	39
95+00	2118	2150	--	32
100+00	2099	2125	--	26
105+00	2074	2100	--	26
110+00	2020	2075	--	55
115+00	2028	2050	--	22
120+00	2014	2025	--	11
125+00	1985	2000	--	15
130+00	1984	1975	9	--
135+00	1966	1950	16	--
140+00	1947	1925	22	--
145+00	1931	1900	31	--

TABLE B-3

District Engineer's Report

Route LR XXXX

County Central Pennsylvania

Type Limited Acess

Station 0+00 to Station 140+00

Length Approximately 3 miles

Width 2-24 Lanes with 12' Climbing Lane WB

Report Prepared December 1977

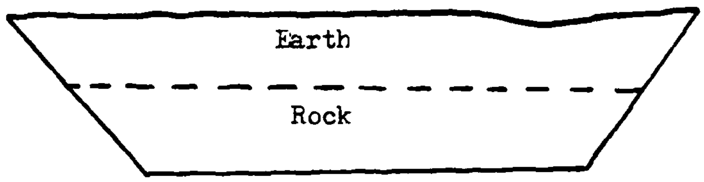
Excavation

Solid Rock	CL - 1	24%
Soft Shale	CL - 1	18%
Loose Rock	CL - 1	0%
Clay	CL - 1	8%
Hard Shale	CL - 1	14%
Earth	CL - 1	36%

APPENDIX C

CONTRACTOR'S ESTIMATE -- BACKGROUND DATA

Station 1+00
(x-section sheet 16)

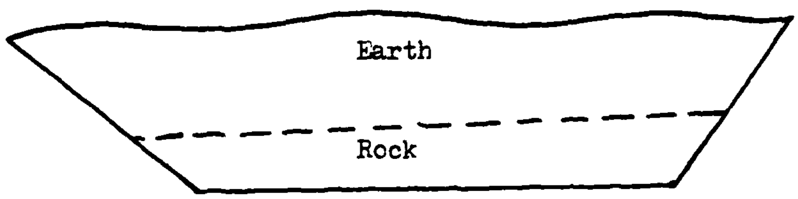


Total Area = 8706 SF

Area of Rock = 6446 SF

Area of Earth = 2260 SF

Station 5+00
(x-section sheet 20)



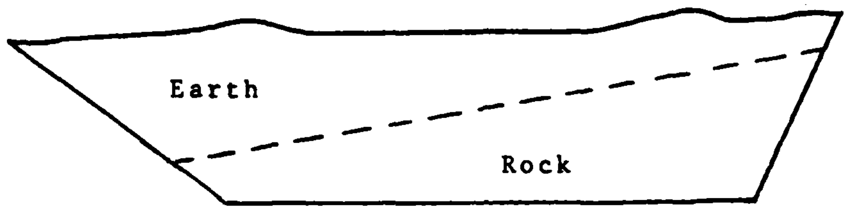
Total Area = 7348 SF

Area of Rock = 2000 SF

Area of Earth = 5348 SF

FIGURE C-1 Contractor's Calculation of Rock Quantity

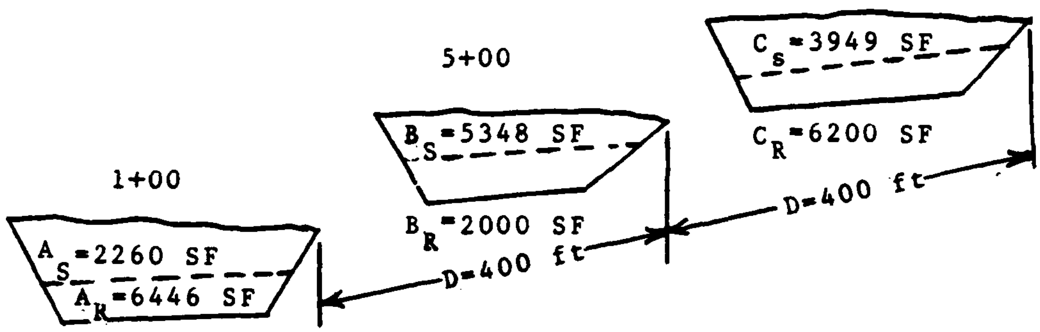
Station 9+00
(x-section sheet 24)



Total Area = 10149 SF

Area of Rock = 6200 SF

Area of Earth = 3949 SF



Using equation (2), page 28, the volumes can be computed as follows:

Soil Volume

$$V_S = \left(\frac{A_S}{2} + B_S + \frac{C_S}{2}\right)D$$

$$= \left(\frac{2260}{2} + 5348 + \frac{3949}{2}\right)(400)$$

$$= 3,381,000 \text{ cf}$$

$$\div 27$$

$$= 125,222 \text{ cy}$$

Rock Volume

$$V_R = \left(\frac{A_R}{2} + B_R + \frac{C_R}{2}\right)D$$

$$= \left(\frac{6446}{2} + 2000 + \frac{6200}{2}\right)(400)$$

$$= 3,329,200 \text{ cf}$$

$$\div 27$$

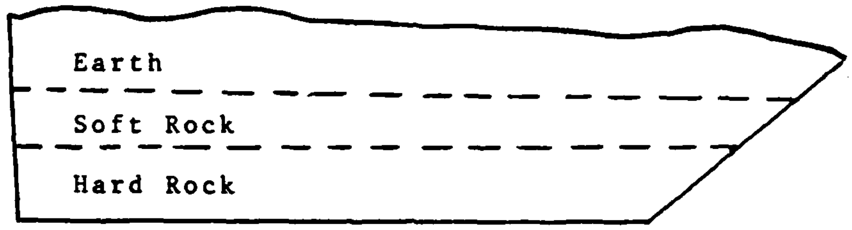
$$= 123,304 \text{ cy}$$

Total Volume 248,526 cy

% Rock = 49.6%

FIGURE C-1 (Continued)
Contractor's Calculation of
Rock Quantity

Station 47+00
(x-section sheet 72)



Total Area = 10190 SF

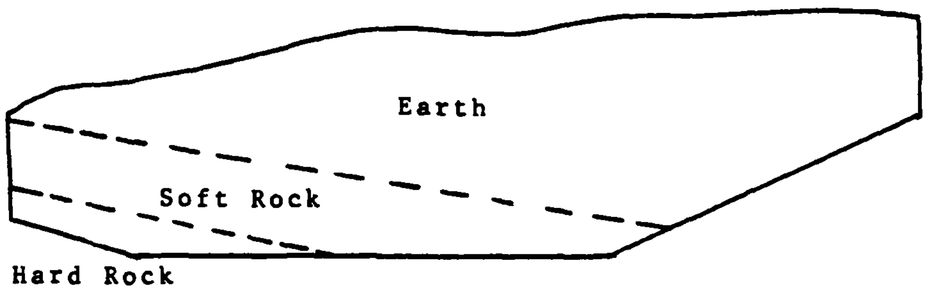
Total Area Rock = 3600 SF

Soft 1810 SF, A_{SR}

Hard 1790 SF, A_{HR}

Area of Earth = 6590 SF (65%), A_S

Station 49+00
(x-section sheet 75)



Total Area = 12392 SF

Total Area Rock = 3500 SF

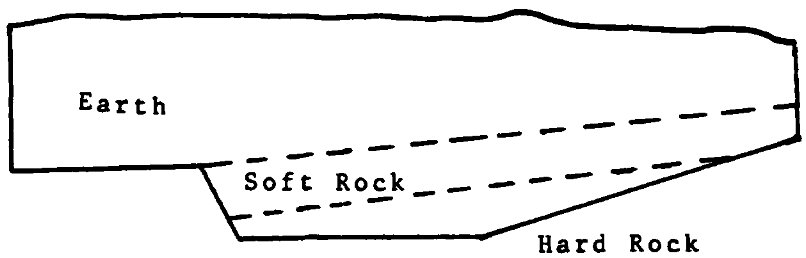
Soft 3425 SF, B_{SR}

Hard 75 SF, B_{HR}

Area of Earth = 8892 Sf (72%), B_S

FIGURE C-2 Contractor's Calculation of
Soft vs. Hard Rock

Stations 53+50 & 54+00
(use 54+00 x-section)
(x-section sheet 86)



Total Area = 16760 SF

Total Area Rock = 7000 SF

Soft 3200, C_{SR}

Hard 3800, C_{HR}

Area of Earth = 9760 SF (58%), C_S

D_1 = 200 ft
D_2 = 500 ft

Again, equation (2) is used to calculate the volumes.

Soil Volume

$$V_S = \left(\frac{A_S}{2} + \frac{B_S}{2}\right) D_1 + \left(\frac{B_S}{2} + \frac{C_S}{2}\right) D_2$$

$$= \left(\frac{6590}{2} + \frac{8892}{2}\right)(200) + \left(\frac{8892}{2} + \frac{9760}{2}\right)(500)$$

$$= 1,548,200 + 4,663,00$$

$$= 6,211,200 \text{ cf}$$

$$= 230,044 \text{ cy}$$

FIGURE C-2 (Continued)
Contractor's Calculation of
Soft vs. Hard Rock

Soft Rock Volume

$$V_{SR} = \left(\frac{A_{SR}}{2} + \frac{B_{SR}}{2}\right)(D_1) + \left(\frac{B_{SR}}{2} + \frac{C_{SR}}{2}\right)(D_2)$$

$$= \left(\frac{1810}{2} + \frac{3425}{2}\right)(200) + \left(\frac{3425}{2} + \frac{3200}{2}\right)(500)$$

$$= 523{,}500 + 1{,}656{,}250$$

$$= 2{,}179{,}750 \text{ cf}$$

$$= 80{,}731 \text{ cy}$$

Hard Rock Volume

$$V_{HR} = \left(\frac{A_{HR}}{2} + \frac{B_{HR}}{2}\right)(D_1) + \left(\frac{B_{HR}}{2} + \frac{C_{HR}}{2}\right)(D_2)$$

$$= \left(\frac{1790}{2} + \frac{75}{2}\right)(200) + \left(\frac{75}{2} + \frac{3800}{2}\right)(500)$$

$$= 186{,}500 + 968{,}750$$

$$= 1{,}155{,}250 \text{ cf}$$

$$= 42{,}787 \text{ cy}$$

Total Volume = 353,562 cy

Earth = 230,044 (65%)

Soft Rock = 80,731 (23%)

Hard Rock = 42,787 cy (12%)

FIGURE C-2 (Continued)
Contractor's Calculation of
Soft vs. Hard Rock

TABLE C-1

Calculation of Average Haul Distance

(Refer to Table 7-8 for Arrow Allocation Diagram)

Avg. Distance Moved (feet)	Quantity (BCY)
500	333,270
	15,017
	28,221
	47,191
	423,699
1500	11,120
	3,169
	9,696
	17,316
	43,521
	138,117
	222,939
2500	34,120
	34,541
	11,229
	98,608
	270,505
	449,003
3500	48,300
	162,229
	335,562
	249,072
	1,899
	78,680
	875,742

TABLE C-1 Continued

Calculation of Average Haul Distance

Avg. Distance Moved (feet)	Quantity (BCY)
4500	16,862
	143,402
	222,791
	298,610
	169,476
	851,141
5500	118,731

$$\text{Avg. Haul} = \frac{500\,(423{,}699) + 1500\,(222{,}939) + 2500\,(449{,}003) + 3500\,(875{,}742) + 4500\,(851{,}141) + 5500\,(118{,}731)}{423{,}699 + 222{,}939 + 449{,}003 + 875{,}742 + 851{,}141 + 118{,}731}$$

$$= \frac{9{,}217{,}017{,}500}{2{,}941{,}272}$$

$$= \underline{\underline{3{,}134 \text{ ft.}}}$$

APPENDIX D

PROPOSED SYSTEM -- BACKGROUND DATA

TABLE D-1

Rock Quantity Information

Section	Total Cut (000 BCY)	Rock Range (%)	Rock Mean (%)	Rock Qty. (BCY)	Rock Std. Dev. (BCY)	LP Rock Qty. (000 BCY)*
1	378.53	30-40	40	151.41	9.46	167.02
2	221.60	32-42	37	81.99	5.54	91.13
3	143.40	32-42	37	53.06	3.59	58.98
4	385.02	32-42	37	142.46	9.63	158.35
5	634.17	35-45	40	253.67	23.67	292.91
6	418.55	35-45	40	167.42	10.46	184.69
13	98.61	30-40	35	34.51	2.47	38.59
14	534.49	30-40	35	187.07	13.36	209.11

* Note: LP Rock Qty. = Rock Qty. + 1.65 x Rock Std. Dev. (for 95% confidence)

<u>Sample Calculation of Three-Value Input Costs</u>

1. The calculation of the input cost estimates for earth (see Table 7-13 -- \$390, \$437, \$517 per 1000 BCY) will be illustrated. The calculation of the haul and compaction input costs follow a similiar procedure.

2. The first step is to average the fleet unit costs appearing on Table 7-11 because it was not known which fleet (loader or scraper) and which shift (day or night) would be used for a particular cut.

$$\text{Avg. Fleet Unit Cost} = \frac{\$1.40+\$1.42+\$1.47+\$1.32+\$1.59}{5}$$

$$= \$1.44/\text{BCY}$$

3. The next step is to apply the factor corresponding to the percentage of the fleet unit cost attributable to earth excavation. Based on the contractor's historical cost records, 30.3% of the total unit cost is accrued by earth excavation. Also, since the input cost data is in terms of 1000 BCY increments, the fleet unit cost is multiplied by 1000.

$$\text{Avg. Earth Excavation Cost} = \$1.44/\text{BCY} \times .303 \times 1000$$

$$= \$436.20 \text{ round up to } \underline{\underline{\$437}} \text{ per 1000 BCY}$$

4. The previous step calculated the middle (mode) value of the 3-value estimate for earth excavation. The final step is to compute the lower and upper values by considering the variable production rates. Referring to

Table 7-10 one can compute the average production.

$$\text{Avg. Fleet Production} = \frac{4{,}300+4{,}300+4{,}150+6{,}000+5{,}000}{5}$$

$$= 4{,}750 \text{ BCY/shift}$$

The lower and upper cost values are calculated based on historical production averages as follows:

$$\text{Lower Value} = \frac{4{,}240 \text{ BCY/shift}}{4{,}750 \text{ BCY/shift}} \times \$437 \text{ per 1000 BCY}$$

$$= \underline{\underline{\$390 \text{ per 1000 BCY}}}$$

$$\text{Upper Value} = \frac{5{,}620 \text{ BCY/shift}}{4{,}750 \text{ BCY/shift}} \times \$437 \text{ per 1000 BCY}$$

$$= \underline{\underline{\$517 \text{ per 1000 BCY}}}$$

TABLE D-2

Sample Input Data

C

SOURCE STATION: 1 DESTINATION STATION: 1

	EXCAVATION COST			HAUL COST			COMPACTION COST		
	L	M	H	L	M	H	L	M	H
EARTH	.0	.0	.0	.0	.0	.0	.0	.0	.0
ROCK	.0	.0	.0	.0	.0	.0	.0	.0	.0
WASTE EARTH	390.0	437.0	517.0	226.0	244.0	273.0	47.0	94.0	118.0
WASTE ROCK	634.0	667.0	766.0	226.0	244.0	273.0	47.0	94.0	118.0
BORROW	.0	.0	.0	.0	.0	.0	.0	.0	.0

SOURCE STATION: 1 DESTINATION STATION: 2

	EXCAVATION COST			HAUL COST			COMPACTION COST		
	L	M	H	L	M	H	L	M	H
EARTH	390.0	437.0	517.0	226.0	244.0	273.0	263.0	282.0	311.0
ROCK	634.0	667.0	766.0	226.0	244.0	273.0	258.0	282.0	311.0
WASTE EARTH	.0	.0	.0	.0	.0	.0	.0	.0	.0
WASTE ROCK	.0	.0	.0	.0	.0	.0	.0	.0	.0
BORROW	.0	.0	.0	.0	.0	.0	.0	.0	.0

SOURCE STATION: 1 DESTINATION STATION: 3

	EXCAVATION COST			HAUL COST			COMPACTION COST		
	L	M	H	L	M	H	L	M	H
EARTH	390.0	437.0	517.0	226.0	244.0	273.0	263.0	282.0	311.0
ROCK	634.0	667.0	766.0	226.0	244.0	273.0	258.0	282.0	311.0
WASTE EARTH	.0	.0	.0	.0	.0	.0	.0	.0	.0
WASTE ROCK	.0	.0	.0	.0	.0	.0	.0	.0	.0
BORROW	.0	.0	.0	.0	.0	.0	.0	.0	.0

SOURCE STATION: 1 DESTINATION STATION: 4

	EXCAVATION COST			HAUL COST			COMPACTION COST		
	L	M	H	L	M	H	L	M	H
EARTH	390.0	437.0	517.0	226.0	244.0	273.0	263.0	282.0	311.0
ROCK	634.0	667.0	766.0	226.0	244.0	273.0	258.0	282.0	311.0
WASTE EARTH	.0	.0	.0	.0	.0	.0	.0	.0	.0
WASTE ROCK	.0	.0	.0	.0	.0	.0	.0	.0	.0
BORROW	.0	.0	.0	.0	.0	.0	.0	.0	.0

TABLE D-3

Objective Function Coefficients

COEFFICIENT	*VARIABLE*
708.85	X(1,1,3)
944.35	X(1,1,4)
1104.37	X(1,2,1)
1444.57	X(1,2,2)
1411.67	X(1,3,1)
1801.02	X(1,3,2)
1718.96	X(1,4,1)
2157.48	X(1,4,2)
2026.25	X(1,5,1)
2550.67	X(1,5,2)
2333.54	X(1,6,1)
2916.32	X(1,6,2)
2640.83	X(1,7,1)
3281.96	X(1,7,2)
2948.12	X(1,8,1)
3583.32	X(1,8,2)
3255.42	X(1,9,1)
3705.48	X(1,9,2)
862.50	X(2,1,3)
1165.20	X(2,1,4)
950.73	X(2,2,1)
1266.34	X(2,2,2)
1104.17	X(2,3,1)
1444.57	X(2,3,2)
1411.67	X(2,4,1)
1801.02	X(2,4,2)
1718.96	X(2,5,1)
2248.11	X(2,5,2)
2026.25	X(2,6,1)
2513.94	X(2,6,2)
2333.54	X(2,7,1)
2870.40	X(2,7,2)
2640.83	X(2,8,1)
3226.86	X(2,8,2)
2948.12	X(2,9,1)
3583.32	X(2,9,2)
3255.42	X(2,10,1)
3939.77	X(2,10,2)
1169.79	X(3,1,3)
1521.66	X(3,1,4)
1104.37	X(3,2,1)
1444.57	X(3,2,2)
950.73	X(3,3,1)
1266.34	X(3,3,2)
1104.37	X(3,4,1)
1444.57	X(3,4,2)
1411.67	X(3,5,1)
1801.02	X(3,5,2)
1718.96	X(3,6,1)
2157.48	X(3,6,2)
2026.25	X(3,7,1)
2513.94	X(3,7,2)

2333.54	X(3,8,1)
2870.40	X(3,8,2)
2640.83	X(3,9,1)
3226.86	X(3,9,2)
2948.12	X(3,10,1)
3583.32	X(3,10,2)
3878.75	X(3,11,1)
4662.84	X(3,11,2)
1477.08	X(4,1,3)
1878.12	X(4,1,4)
1411.67	X(4,2,1)
1801.02	X(4,2,2)
1104.37	X(4,3,1)
1444.57	X(4,3,2)
950.62	X(4,4,1)
1266.34	X(4,4,2)
1182.29	X(4,5,1)
1534.95	X(4,5,2)
1567.50	X(4,6,1)
1981.79	X(4,6,2)
1952.71	X(4,7,1)
2428.63	X(4,7,2)
1710.83	X(4,7,3)
2149.27	X(4,7,4)
2337.92	X(4,8,1)
2875.47	X(4,8,2)
2723.12	X(4,9,1)
3322.32	X(4,9,2)
3108.33	X(4,10,1)
3769.16	X(4,10,2)
3493.54	X(4,11,1)
4216.00	X(4,11,2)
3878.75	X(4,12,1)
4662.84	X(4,12,2)
1784.37	X(5,1,3)
2234.57	X(5,1,4)
1718.96	X(5,2,1)
2157.48	X(5,2,2)
1411.67	X(5,3,1)
1801.02	X(5,3,2)
1104.37	X(5,4,1)
1444.57	X(5,4,2)
950.73	X(5,5,1)
1266.34	X(5,5,2)
1258.54	X(5,6,1)
1623.40	X(5,6,2)
1720.00	X(5,7,1)
2158.69	X(5,7,2)
1478.12	X(5,7,3)
1879.32	X(5,7,4)
2181.46	X(5,8,1)
2693.98	X(5,8,2)

2642.92	X(5,9,1)
3229.27	X(5,9,2)
3104.37	X(5,10,1)
3764.57	X(5,10,2)
3565.83	X(5,11,1)
4299.86	X(5,11,2)
4027.29	X(5,12,1)
4835.15	X(5,12,2)
4488.75	X(5,13,1)
5370.44	X(5,13,2)
1718.96	X(6,3,1)
2157.48	X(6,3,2)
1411.67	X(6,4,1)
1801.02	X(6,4,2)
1104.37	X(6,5,1)
1444.57	X(6,5,2)
950.73	X(6,6,1)
1266.34	X(6,6,2)
1026.87	X(6,7,1)
1354.67	X(6,7,2)
785.00	X(6,7,3)
1075.30	X(6,7,4)
1256.67	X(6,8,1)
1621.22	X(6,8,2)
1486.46	X(6,9,1)
1887.78	X(6,9,2)
2337.92	X(6,10,1)
2875.47	X(6,10,2)
2723.12	X(6,11,1)
3322.32	X(6,11,2)
3108.33	X(6,12,1)
3769.16	X(6,12,2)
3493.54	X(6,13,1)
4216.00	X(6,13,2)
1258.54	X(7,6,1)
950.73	X(7,7,1)
708.85	X(7,7,3)
1104.37	X(7,8,1)
1411.67	X(7,9,1)
1718.96	X(7,10,1)
2336.87	X(7,11,1)
2723.12	X(7,12,1)
1460.42	X(8,6,1)
1128.75	X(8,7,1)
886.87	X(8,7,3)
962.92	X(8,8,1)
1107.92	X(8,9,1)
1460.42	X(8,10,1)
1952.71	X(8,11,1)
2337.92	X(8,12,1)
2723.12	X(8,13,1)
1411.67	X(9,7,1)

1169.79	X(9,7,3)
1780.83	X(9,7,5)
1104.37	X(9,8,1)
1215.21	X(9,8,5)
950.73	X(9,9,1)
1044.90	X(9,9,5)
1157.92	X(9,10,1)
1290.21	X(9,10,5)
1567.50	X(9,11,1)
1169.79	X(9,11,3)
1780.83	X(9,11,5)
1952.71	X(9,12,1)
2271.46	X(9,12,5)
2337.92	X(9,13,1)
2762.08	X(9,13,5)
3252.71	X(9,14,5)
1718.96	X(10,7,1)
1411.67	X(10,8,1)
1104.37	X(10,9,1)
950.73	X(10,10,1)
1157.92	X(10,11,1)
862.50	X(10,11,3)
1411.67	X(10,12,1)
1718.96	X(10,13,1)
2337.92	X(11,7,1)
1952.71	X(11,8,1)
1567.50	X(11,9,1)
1104.37	X(11,10,1)
973.33	X(11,11,1)
708.85	X(11,11,3)
1104.37	X(11,12,1)
1411.67	X(11,13,1)
1668.96	X(11,14,1)
2333.54	X(12,7,1)
2026.25	X(12,8,1)
1718.96	X(12,9,1)
1411.67	X(12,10,1)
1157.92	X(12,11,1)
862.50	X(12,11,3)
950.73	X(12,12,1)
1104.37	X(12,13,1)
1411.67	X(12,14,1)
3108.33	X(13,7,1)
3769.16	X(13,7,2)
2723.12	X(13,8,1)
3322.32	X(13,8,2)
2337.92	X(13,9,1)
2875.47	X(13,9,2)
1718.96	X(13,10,1)
2157.48	X(13,10,2)
1411.67	X(13,11,1)
1801.02	X(13,11,2)

1169.79	X(13,11,3)
1104.37	X(13,12,1)
1210.27	X(13,12,2)
950.73	X(13,13,1)
1266.34	X(13,13,2)
1104.37	X(13,14,1)
1444.57	X(13,14,2)
3493.54	X(14,7,1)
4216.00	X(14,7,2)
3108.33	X(14,8,1)
3769.16	X(14,8,2)
2723.12	X(14,9,1)
3322.32	X(14,9,2)
1839.58	X(14,10,1)
2297.41	X(14,10,2)
1578.96	X(14,11,1)
1995.08	X(14,11,2)
1337.08	X(14,11,3)
1715.72	X(14,11,4)
1318.33	X(14,12,1)
1692.76	X(14,12,2)
1057.71	X(14,13,1)
1390.43	X(14,13,2)
927.40	X(14,14,1)
1239.27	X(14,14,2)

Computation of Fractional Compatibility

This appendix illustrates how the fractional compatibility, discussed on page 126, between the simulation and LP sensitivity ranges is calculated. Although only one example variable is shown, the same procedure applies to every variable appearing in Table 7-15.

Variable	Coefficient Ranges: Simulation / LP Sensitivity
X(4,8,1)	2182 - 2478 / 2194 - 2366

Simulation statistics on variable:

(provided by proposed system)

Maximum	2477.85
Minimum	2182.23
Average	2312.37
Std. Dev.	60.34
Range	295.62
No. Obs.	100.00

The average and standard deviation are used to compute the appropriate Z factors (and hence, the resultant area) for the simulation range.

The general form of the equation used is

$$Z_i = \frac{\text{LP Limits Average}}{\text{Std. Dev.}}$$

Lower range:

$$Z_L = \frac{-2194 + 2312.37}{60.34} = 1.96$$

Upper range:

$$Z_U = \frac{2366 - 2312.37}{60.34} = 0.89$$

Areas (from standard normal tables):

$$Z_L \ \text{area}_L = 0.475$$

$$Z_U \ \text{area}_U = 0.313$$

$$\begin{aligned} \text{Total area} &= \text{area}_L + \text{area}_U \\ &= 0.475 \\ &= 0.788 \end{aligned}$$

The total area common to both ranges is therefore 0.79 or 79% for this variable. This is the fractional compatibility shown in Table 7-15 for this variable.

APL Listing of Input/Output Example

```
        MENU

A:  DESCRIBE PROGRAM
B:  ENTER COST DATA FOR LP SOLUTION
C:  DISPLAY ALL COST DATA FOR LP SOLUTION
D:  DISPLAY COST DATA FOR A SINGLE COEF
E:  EDIT COST DATA FOR LP SOLUTION
F:  DISPLAY COST COEF FOR LP SOLUTION
G:  SIMULATE COST COEF FROM LP SOLUTION
H:  DISPLAY SIMULATED TOTAL UNIT COST
I:  PERCENTILES OF TOTAL UNIT COST
J:  PLOT CUMULATIVE TOTAL UNIT COST

ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.
 A

    THIS WORKSPACE, NAMED HOPE FOR HIGHWAY OPTIMIZATION
PROGRAM FOR ESTIMATING, CONTAINS THE FUNCTIONS
NEEDED TO ESTIMATE THE EARTHWORK PORTION OF A HIGHWAY
PROJECT USING THE SYSTEM DEVELOPED BY F. UHLIK AS PART OF
HIS PH D DISSERTATION IN CIVIL ENGINEERING.

  THE VARIOUS FUNCTIONS INCLUDED IN THIS PROGRAM ALLOW THE
USER TO COMBINE PROABILISTIC ESTIMATING WITH LINEAR PROGRAMMING
OPTIMIZATION TO OBTAIN A PROBABILITY DISTRIBUTION FOR THE
TOTAL UNIT COST OF THE EARTHWORK ESTIMATE.

  NO KNOWLEDGE OF THE APL LANGUAGE IS REQUIRED TO USE THIS
PROGRAM.

  IF A PROBLEM OCCURS WHILE WORKING WITH THIS SYSTEM,TYPE HELP
IN ORDER TO RECEIVE INSTRUCTIONS.

  TYPE MENU TO BEGIN USING THE PROGRAM OR INPUT FOR A
DESCRIPTION OF HOW DATA MAY BE ENTERED IN THIS SYSTEM.

ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.
```

```
R
DO YOU WANT TO SAVE ANY EXISTING DATA?.YES
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .1
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .3
       ENTER EXCAVATION COST ESTIMATE(S): .390 437 517
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .47 94 118
       DO YOU HAVE MORE DATA? .Y
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .1
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .4
       ENTER EXCAVATION COST ESTIMATE(S): .634 667 766
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .47 94 118
       DO YOU HAVE MORE DATA? .Y
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .2
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .1
       ENTER EXCAVATION COST ESTIMATE(S): .390 437 517
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .263 282 311
       DO YOU HAVE MORE DATA? .Y
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .2
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .2
       ENTER EXCAVATION COST ESTIMATE(S): .634 667 766
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .258 282 311
       DO YOU HAVE MORE DATA? .Y
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .3
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .1
       ENTER EXCAVATION COST ESTIMATE(S): .390 437 517
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .263 282 311
       DO YOU HAVE MORE DATA? .Y
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .3
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .2
       ENTER EXCAVATION COST ESTIMATE(S): .634 667 766
       ENTER HAUL COST ESTIMATE(S):       .226 244 273
       ENTER COMPACTION COST ESTIMATE(S): .258 282 311
       DO YOU HAVE MORE DATA? .N
ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.
```

```
D
ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .1

                EXCAVATION COST          HAUL COST         COMPACTION COST
             -------------------- -------------------- --------------------
EARTH              .0      .0      .0      .0      .0      .0      .0      .0      .0
ROCK               .0      .0      .0      .0      .0      .0      .0      .0      .0
WASTE EARTH  390.0   437.0   517.0   226.0   244.0   273.0    47.0    94.0   118.0
WASTE ROCK   634.0   667.0   766.0   226.0   244.0   273.0    47.0    94.0   118.0
BORROW             .0      .0      .0      .0      .0      .0      .0      .0      .0

SHRINKAGE FACTORS
     S [1,1] = 1.25 1.25 1.25
     S [1,2] = 1.45 1.45 1.45
     S [1,3] = 1.25 1.25 1.25
     S [1,4] = 1.25 1.25 1.25
     S [1,5] = 1.45 1.45 1.45
ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.


 E

ENTER SOURCE STATION:      .1
ENTER DESTINATION STATION: .1
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW: .1

ENTER TYPE OF DATA TO BE CHANGED( OR THE NUMERAL 0 TO EXIT):

 1 =SWELL/SHRINKAGE FACTOR
 2 EXCAVATION COST
 3 =HAUL COST
 4 =COMPACTION COST
 5 =MOVE TO ANOTHER STATION


ENTER ONE NUMBER PLEASE (0=EXIT,¯1=TABLE OF OPTIONS): .2
ENTER EXCAVATION COST ESTIMATE(S): .390 437 517

ENTER ONE NUMBER PLEASE (0=EXIT,¯1=TABLE OF OPTIONS): .0

DON'T FORGET TO TYPE )SAVE TO SAVE THE CHANGES YOU JUST MADE
ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.
```

COEFFICIENT	VARIABLE
708.85	X(1,1,3)
944.35	X(1,1,4)
1104.37	X(1,2,1)
1444.57	X(1,2,2)
1411.67	X(1,3,1)
1801.02	X(1,3,2)
1718.96	X(1,4,1)
2157.48	X(1,4,2)
2026.25	X(1,5,1)
2550.67	X(1,5,2)
2333.54	X(1,6,1)
2916.32	X(1,6,2)
2640.83	X(1,7,1)
3281.96	X(1,7,2)
2948.12	X(1,8,1)
3583.32	X(1,8,2)
3255.42	X(1,9,1)
3705.48	X(1,9,2)
862.50	X(2,1,3)
1165.20	X(2,1,4)
950.73	X(2,2,1)
1266.34	X(2,2,2)
1104.17	X(2,3,1)
1444.57	X(2,3,2)
1411.67	X(2,4,1)
1801.02	X(2,4,2)
1718.96	X(2,5,1)
2248.11	X(2,5,2)
2026.25	X(2,6,1)
2513.94	X(2,6,2)
2333.54	X(2,7,1)
2870.40	X(2,7,2)
2640.83	X(2,8,1)
3226.86	X(2,8,2)
2948.12	X(2,9,1)
3583.32	X(2,9,2)
3255.42	X(2,10,1)
3939.77	X(2,10,2)
1169.79	X(3,1,3)
1521.66	X(3,1,4)
1104.37	X(3,2,1)
1444.57	X(3,2,2)
950.73	X(3,3,1)
1266.34	X(3,3,2)
1104.37	X(3,4,1)
1444.57	X(3,4,2)
1411.67	X(3,5,1)
1801.02	X(3,5,2)
1718.96	X(3,6,1)
2157.48	X(3,6,2)
2026.25	X(3,7,1)

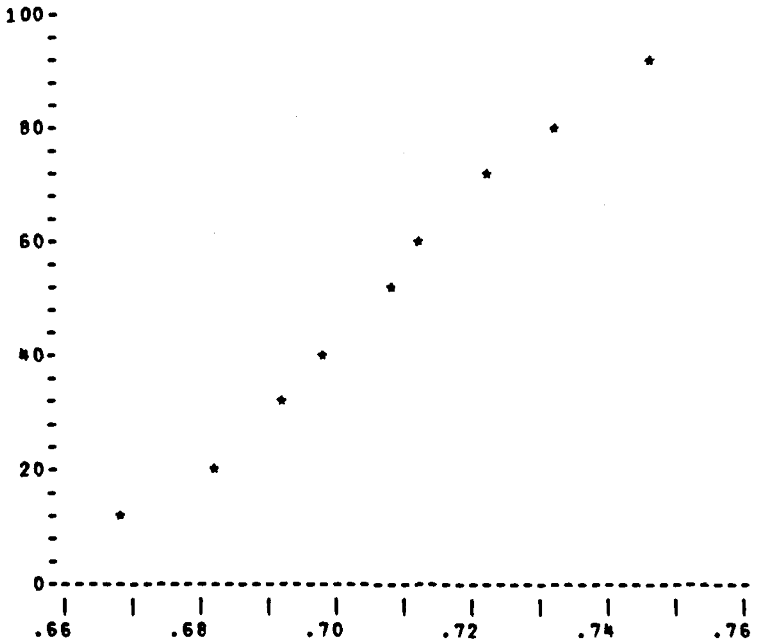
```
G
ENTER NUMBER OF REPLICATIONS: .100
ENTER CONFIDENCE FACTOR:      .67

ENTER SOURCE STATION:       .1
ENTER DESTINATION STATION: .1
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW.3
ENTER STATION QUANTITY OF MATERIAL: .211.51
COEF X[113]:   LOW   625.373451          HIGH:   774.013093

DO YOU WANT STATISTICS ON THIS COEFICIENT?.Y

MAXIMUM 774.013093
MINIMUM 625.373451
AVERAGE 695.6685439
STD.DEV 28.1869324
RANGE   148.6396421
NO. OBS 100

   95 PERCENT CONFIDENCE INTERVAL IS 640.4221564 - 750.9149314

THE PERT  STD DEV OF THE COST COEFFICIENT IS 26.2828911


ARE THERE ANY MORE STATIONS?.Y

ENTER SOURCE STATION:       .1
ENTER DESTINATION STATION: .1
ENTER 1=EARTH,2=ROCK,3=WASTE EARTH,4=WASTE ROCK,5=BORROW.4
ENTER STATION QUANTITY OF MATERIAL: .11.36
COEF X[114]:   LOW   867.0590984          HIGH:   1061.326647

DO YOU WANT STATISTICS ON THIS COEFICIENT?.N

ARE THERE ANY MORE STATIONS?.N


THE AVERAGE TOTAL UNIT COST IS 0.7076110958


THE TOTAL QUANTITY IN BCY IS 222870

THE AVERAGE HAUL DISTANCE IN FEET IS 500
ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.
```

```
 H
MAXIMUM 0.7886578724
MINIMUM 0.6376925112
AVERAGE 0.7076110958
STD.DEV 0.02856919253
RANGE   0.1509653612
NO. OBS 100


DO YOU WANT TO SEE THE PERT STD DEV?.Y

THE PERT STD DEV IS 0.02498103599

DO YOU WANT TO SEE ALL 100 VALUES OF THE SIMULATED UNIT COST?.N
ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):
.

 I
NOTE BE SURE TO RUN THE SIMULATION(MENU OPTION G BEFORE
ATTEMPTING TO OBTAIN PERCENTILES OF THE TOTAL UNIT COST

DID YOU ALREADY RUN THE SIMULATION?.Y
   PERCENT  UPPER LIMIT    AMOUNT
     10.00        .67        10
     20.00        .68        20
     30.00        .69        30
     40.00        .70        40
     50.00        .71        50
     60.00        .71        60
     70.00        .72        70
     80.00        .73        80
     90.00        .75        90

THE LOWER QUARTILE IS:    0.68647
THE UPPER QUARTILE IS:    0.72453

ENTER NEW PERCENTS,OR 0 TO TERMINATE
.85 95
   PERCENT  UPPER LIMIT    AMOUNT
     85.00        .74        85
     95.00        .75        95

THE LOWER QUARTILE IS:    0.68647
THE UPPER QUARTILE IS:    0.72453

ENTER NEW PERCENTS,OR 0 TO TERMINATE
 0
```

J

NOTE: BE SURE TO RUN THE SIMULATION(MENU OPTION G BEFORE
ATTEMPTING TO PLOT THE TOTAL UNIT COST

DID YOU ALREADY RUN THE SIMULATION?.Y



ENTER LETTER OF OPTION OR THE NUMERAL 0 TO EXIT(CR=MENU TABLE):

.

0

APPENDIX E

SEMCAP Estimate -- Computer Listing

```
       RIPPING
ENTER TOTAL QUANTITY OF EARTH TO BE RIPPED (BCY) : 600000

ENTER NUMBER OF TRACTORS RIPPING : 2
ENTER RIPPER SHANK SPACING (INCHES) :
***NO TABLE ENTERED. SORRY  ***
ENTER RIPPER SHANK SPACING (INCHES) : 24
ENTER RIPPER SHANK PENETRATION DEPTH (INCHES) : 15
ENTER LENGTH OF RIPPER PASS (FEET) : 200

ENTER CRAWLER TRAVEL SPEED (MPH) : 3

ENTER MANUVER TIME REQUIRED PER CYCLE (MINUTES) :  5

ENTER RIPPER EFFICIENCY FACTOR (MIN. OR DECIMAL) :  85
 SUMMARY OF RIPPING:
ACTUAL RIPPER PRODUCTION = 1502 BCY/HR.
***NOTE: REF. CATERPILLAR HANDBOOK
         PRODUCTION IN THE FIELD IS USUALLY 10 TO 20 PERCENT
         LOWER THAN "CALCULATED" PRODUCTION
ENTER PERCENT REDUCTION DESIRED (IF: 10 PERCENT= 10):  .15
ENTER OWNING AND OPERATING COST (INCL. OPERATOR (/HR/UNIT) :  82
         RIPPING SUMMARY
 QUANTITY          =        600000  BCY
 NUM OF TRACTORS   =             2
 PRODUCTION RATE   =       1276.71  BCY/HR.
 DURATION          =           470  HOURS
 LOOSENING COSTS   =          .128  /BCY.
 PROJECT COST      =      77073.29

  **-END RIPPING-**
```

```
      SCRAPER
ENTER TOTAL QUANTITY OF EARTH TO BE MOVED BY SCRAPERS (BCY) :  1764763
ENTER BANK DENSITY OF MATERIAL : .3500
ENTER LOOSE DENSITY OF MATERIAL : .2800
ENTER HEAPED SCRAPER VOLUME (LCY) : .31
ENTER MAXIMUM SCRAPER PAYLOAD (LBS) : .75000
ENTER PERCENT OF HEAP CAP;REF LOAD GROWTH CURVE 80°/°=80) :  71
ENTER SCRAPER LOAD TIME (MIN.) : . 6
ENTER TIME FOR MANUVERING  DUMPING, SPOTTING AND DELAYS (MIN.) :  7
GENERAL NOTE:
INPUT ROAD SEGMENTS LENGTHS, HAUL SPEEDS AND SPEED FACTORS
FROM LOAD AREA (CUT) TO DUMP
ENTER LENGTH OF EACH HAUL ROAD SEGMENT (FT) : .700 2500
ENTER MAX HAUL SPEED ( 53250 LBS PAYLOAD) FOR EACH ROAD SEGMENT (MPH) :  8 12
ENTER HAUL SPEED FACTOR (ACCEL/DECELERATION) FOR EACH ROAD SEGMENT :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE:  . 6 .75
GENERAL NOTE:
INPUT RETURN SPEEDS AND SPEED FACTORS.
BEGIN WITH THE ROAD SEGMENT ORIGINATING FROM THE DUMP AREA
ENTER MAX RETURN (EMPTY) SPEED FOR EACH ROAD SEGMENT (MPH) : .15 12
ENTER RETURN SPEED FACTOR (ACCEL/DECELERATION) FOR EACH ROAD SEGMENT :
  IF DESIRED  HIT RETURN FOR INFORMATION TABLE:  . 75  6
ENTER NUMBER OF PUSHERS AVAILABLE (ZERO, IF PUSH-PULL LOADING):   3
ENTER SINGLE(1) OR TANDEM (2) PUSHING : .1
ENTER BACKTRACK 1), CHAIN(2), OR SHUTTLE LOADING(3) : .1
```

```
CALCULATED VALUES ARE:
   SCRAPER CYCLE TIME              =    9.74 MINUTES
   PUSHER CYCLE TIME(CATERPILLAR)=    1.09 MINUTES
   PUSHER CYCLE TIME(INT/TEREX)  =     .90 MINUTES

ENTER DESIRED PUSHER CYCLE TIME (MIN.):   1.09

  8.9 SCRAPERS CAN BE SUPPORTED BY ONE PUSHER SET
                              ***SINGLE OPERATION ***
    TO ACHIEVE FLEET BALANCE 27 SCRAPERS ARE NEEDED

ENTER NUMBER OF SCRAPERS TO BE USED : 10
ENTER SCRAPER EFFICIENCY FACTOR (MIN. OR DECIMAL) : . 85
ENTER SCRAPER OWNING + OPERATIG COST. INCL OPERATOR (□/HR/UNIT) :  78.56
ENTER PUSHER OWNING + OPERATING COST. INCL OPERATOR (□/HR/UNIT) :  81.33
SCRAPER PROGRAM SUMMARY
NUM. OF SCRAPERS =            10
NUM. OF PUSHERS  =             3
FLEET PRODUCTION =           796      BCY/HR
PROJECT DURATION =          2217      HOURS
UNIT COST        =             1.293 /BCY
PROJECT COST     =       2281838.56

SCRAPER CYCLE TIME =    9.74 MIN
PUSHER CYCLE TIME  =    2.92 MIN

 .  **-END SCRAPER-**
```

```
    FELOADER
ENTER RECOMMENDED LOADER MAX OPERATING CAPACITY (LBS) :
                                                          40500
ENTER LOADER BUCKET FILL FACTOR :
  IF DESIRED  HIT RETURN FOR INFORMATION TABLE: .

     LOADER BUCKET FILL FACTOR (CATERPILLAR)
*************************************************
LOOSE MATERIAL SIZE                       FILL FACTOR
 MIXED MOIST AGGREGRATES                   95 TO 1.00
 UNIFORM AGGREGATES UP TO 1/8 INCH        .95    1.00
 1/8 TO 3/8 INCH                           85      90
 1/2 TO 3/4 INCH                           90      95
 1 INCH AND OVER                           85      90

BLASTED MATERIAL
 WELL BLASTED                              80      85
 AVERAGE                                   75      80
 POORLY BLASTED                            60      65
*************************************************
ENTER LOADER BUCKET FILL FACTOR :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE: . 75
MAX ALLOWABLE BUCKET SIZE = 14.46 CY
ENTER NEXT SMALLEST BUCKET SIZE TO FIT LOADER:  13 5
ENTER TOTAL FIXED CYCLE TIME, EXCLUDING TRAVEL TIME (MIN.) :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE:
```

```
            FIXED TIMES FOR FRONT END LOADERS
*************************************************************
REF: CATERPILLAR HANDBOOK
BASIC CYCLE TIME ELEMENT        .4 MINUTE
VARIABLE CYCLE TIME ELEMENTS  ADD(+) OR SUBTRACT(-)
                              FROM BASIC CYCLE
MATERIALS                        PILE
 MIXED              + .02        CONVEYOR OR DOZER PILED
 UP TO 1/8 INCH     + .02         (10 FEET AND UP)        00
 1/8 TO 3/4 INCH    -  02          10 FEET OR LESS)    +  01
 3/4 TO 6 INCHES      .00        DUMPED BY TRUCK       + .02
 6 INCHES AND OVER + .03 AND UP
 BANK AND BROKEN   + .04 AND UP

MISCELLANEOUS
 COMMON OWNERSHIP, TRUCK AND LOADERS   UP TO - .04
 INDEPENDENTLY OWNED TRUCKS            UP TO + .04
 CONSTANT OPERATION                    UP TO -  04
 INCONSISTENT OPERATION                UP TO + .04
 SMALL TARGET                          UP TO +  04
 FRAGILE TARGET                        UP TO +  05

*************************************************************
ENTER TOTAL FIXED CYCLE TIME  EXCLUDING TRAVEL TIME (MIN.) :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE: . 43
ENTER LOADER HAUL DISTANCE (FT):     50
ENTER HAUL SPEED (2ND GEAR FORWARD MPH) : .3
ENTER RETURN SPEED (3RD GEAR REVERSE  MPH) : .4
ENTER LOADER EFFICIENCY FACTOR (MIN. OR DECIMAL) :    85
ENTER LOADER OWNING + OPERATING COST  INCL  OPERATOR  /HP) :  116 42

          FRONT END LOADER SUMMARY
IDEAL LOADER PRODUCTION  =     576 BCY/HR
ACTUAL LOADER PRODUCTION =     490 BCY/HR
LOADING UNIT COST        =    .238 /BCY

   **-END FELOADER-**
```

```
     TRUCK
ENTER MAXIMUM VEHICLE VOLUME (LCY) :
                                         50
ENTER MAXIMUM VEHICLE PAYLOAD (TONS) : 85

ENTER SIZE OF LOADER BUCKET (CY) : 13.5

ENTER BUCKET FILL FACTOR : .75
ENTER IDEAL LOADING RATE (BCY/HR) : 576

ENTER FIXED TIME TO TURN, DUMP, SPOT AND MANUVER (MIN.) :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE:

    FIXED TIMES FOR TRUCKS
*********************************
CATERPILLAR REFERENCE DATA
EXCHANGE TIME = .6 TO .8 MIN.
MANUVER AT DUMP AND TURN = 1.0MIN
*********************************
TEREX REFERENCE TABLE
OPERATING         TURN AND      SPOT
CONDITIONS        DUMP TIME     TIME
FAVORABLE            1.00         15
AVERAGE              1.30        .30
UNFAVORABLE          1.75         50
*********************************
EUCLID REFERENCE TABLE
OPERATING         TURN AND      SPOT
CONDITIONS        DUMP TIME     TIME
FAVORABLE             .70         15
AVERAGE              1.00        .30
UNFAVORABLE          1.50         50
*********************************
ENTER FIXED TIME TO TURN, DUMP, SPOT, AND MANUVER (MIN.) :
  IF DESIRED, HIT RETURN FOR INFORMATION TABLE: 1.6
```

```
GENERAL NOTE:
INPUT ROAD SEGMENT LENGTHS  HAUL SPEEDS AND SPEED FACTORS
FROM LOAD AREA (CUT) TO DUMP
ENTER LENGTH OF EACH HAUL ROAD SEGMENT (FT) : .700 2500
ENTER MAX HAUL SPEED (113400 LBS PAYLOAD) FOR EACH ROAD SEGMENT (MPH) :  25 30
ENTER HAUL SPEED FACTOR (ACCEL/DECELERATIION) FOR EACH ROAD SEGMENT :
  IF DESIRED. HIT RETURN FOR INFORMATION TABLE:

                 SPEED FACTORS (INTERNATIONAL)
***************************************************************
LENGTH OF HAUL    STARTING FROM OR COMING    MOVING WHEN ENTERING
ROAD IN FEET      TO STOP IN HAUL SECTION     HAUL ROAD SECTION
  200   500 .........   .33 -  .51  .. .  . ...     56 -  .80
  501  1000 .........   .43 -  .67  ....... ..      65 -   83
 1001  1500 .........    53 -  .75  ..........      78 -   90
.1501  2000 .........    59 -  .80  .......   .     84 -   93
 2001  2500 .........   .62 -  .84  .......   .     88 -  .95
 2501  3000 .. .  .      65 -   85  .......   .     90 -   97
 3001  3500 .........   .68 -  .87  ....      .     92 - 1.00
 3501  UP   . .......   .70 -  .95  ..   ......     95 - 1.00
***************************************************************
ENTER HAUL SPEED FACTOR (ACCEL/DECELERATIION) FOR EACH ROAD SEGMENT :
  IF DESIRED. HIT RETURN FOR INFORMATION TABLE:  ..6 .75
GENERAL NOTE:
INPUT RETURN SPEEDS AND SPEED FACTORS.
BEGIN WITH ROAD SEGMENT ORIGINATING FROM THE DUMP AREA
ENTER MAX RETURN SPEED (EMPTY) FOR EACH ROAD SEGMENT (MPH) : .37
                                                              37 3
                                                                 20
ENTER RETURN SPEED FACTOR (ACCEL/DECELERATION) FOR EACH ROAD SEGMENT :
  IF DESIRED. HIT RETURN FOR INFORMATION TABLE:  . 75  6
```

```
SHOVEL/LOADER CAN SUPPORT     2.51 TRUCKS
ENTER NUMBER OF TRUCKS TO BE USED : .4

ENTER TRUCK EFFICIENCY FACTOR (MIN. OR DECIMAL) :    85
ENTER TRUCK OWNING AND OPERATING COST  INCL  DRIVER ($/HR/UNIT) :  65
         TRUCK SUMMARY
NUMBER OF TRUCKS                  =      4
TRUCK CAPACITY                    =     32 BCY
IDEAL TRUCK FLEET PRODUCTION      =    576 BCY/HR
ACTUAL TRUCK FLEET PRODUCTION     =   .531 BCY/HR
TRUCKING UNIT COST                =   .531 /BCY

      **-END TRUCK-**
```

```
     LOADHAUL
ENTER TOTAL AMOUNT OF EARTH TO BE MOVED (BCY) :  1176509
ENTER METHOD OF LOADING;  1)IF BY POWER SHOVEL   2)IF BY FRONT END LOADER :  2

     ********** FRONT END LOADER ANALYSIS **********

MAX ALLOWABLE BUCKET SIZE = 14.46 CY
ENTER NEXT SMALLEST BUCKET SIZE TO FIT LOADER:   13 5

         FRONT END LOADER SUMMARY
IDEAL LOADER PRODUCTION  =    576 BCY/HR
ACTUAL LOADER PRODUCTION =    490 BCY/HR
LOADING UNIT COST        =    238 /BCY

   **-END FELOADER-**


          ********** TRUCK ANALYSIS **********

ENTER MAX HAUL SPEED (113400 LBS PAYLOAD) FOR EACH ROAD SEGMENT (MPH) : .25 30
ENTER HAUL SPEED FACTOR (ACCEL/DECELERATION) FOR EACH ROAD SEGMENT :
  IF DESIRED. HIT RETURN FOR INFORMATION TABLE:   6  75
ENTER MAX RETURN SPEED (EMPTY) FOR EACH ROAD SEGMENT (MPH) :  37 20
ENTER RETURN SPEED FACTOR (ACCEL/DECELERATION) FOR EACH ROAD SEGMENT :
  IF DESIRED. HIT RETURN FOR INFORMATION TABLE:    75 .6

SHOVEL/LOADER CAN SUPPORT    2.51 TRUCKS
ENTER NUMBER OF TRUCKS TO BE USED : .4

         TRUCK SUMMARY
NUMBER OF TRUCKS                =      4
TRUCK CAPACITY                  =     32 BCY
IDEAL TRUCK FLEET PRODUCTION    =    576 BCY/HR
ACTUAL TRUCK FLEET PRODUCTION   =   .531 BCY/HR
TRUCKING UNIT COST              =   .531 /BCY

      **-END TRUCK-**
```

```
ENTER LOAD HAUL FLEET EFFICIENCY FACTOR (MIN. OR DECIMAL) :   85

    LOAD HAUL SUMMARY

         FRONT END LOADER SUMMARY
IDEAL LOADER PRODUCTION  =    576 BCY/HR
ACTUAL LOADER PRODUCTION =    490 BCY/HR
LOADING UNIT COST        =   .238 /BCY

         TRUCK SUMMARY
NUMBER OF TRUCKS                =      4
TRUCK CAPACITY                  =     32 BCY
IDEAL TRUCK FLEET PRODUCTION    =    576 BCY/HR
ACTUAL TRUCK FLEET PRODUCTION   =   .531 BCY/HR
TRUCKING UNIT COST              =   .531 /BCY

********* LOADER-HAULER SUMMARY *********
LOADING BY FRONT END LOADER
NUMBER OF TRUCKS              =            4
ACTUAL FLEET PRODUCTION       =          417 BCY/HR
LOAD-HAUL PROJECT DURATION    =         2825 HOURS
LOAD-HAUL PROJECT COST        =      1063293
LOAD-HAUL UNIT COST           =         .904 /BCY
  **-END LOADHAUL-**
```

```
      COMPACT
    ***** COMPACTION ANALYSIS *****
ENTER WIDTH OF DRUM (FT) : .3
ENTER DEPTH OF SOIL LAYER AFTER COMPACTION (INCHES) :  15
ENTER AVERAGE GROUND SPEED OF COMPACTOR (MPH) :  3.5
ENTER NUMBER OF PASSES TO OBTAIN REQUIRED DENSITY : .4
ENTER TRACTOR EFFICIENCY FACTOR (MIN. OR DECIMAL) :   85
ENTER NUMBER OF COMPACTION UNITS : .1
DIMENSIONS OF THE FILL : LENGTH  WIDTH, DEPTH (FT):   9360 750 10
ENTER COMPACTION UNIT OWNING + OPERATING COST (INCLG OPER
/HR) : .57.55
ENTER NUMBER OF FILL SPREADING UNITS (GRADERS) :  1
ENTER IDEAL PRODUCTION RATE OF ONE SPREADER (CY/HR) : .750
ENTER SPREADER EFFICIENCY FACTOR (MIN. OR DECIMAL) :   85
ENTER SPREADER UNIT OWNING + OPERATING COST. INCL. OPER. :  50 37


DOMAIN ERROR
CSUMMARY[9]  COUT 'COMPACTION TOTAL COST    =  '  8 2 ▼(COMTOTALCOST)) '  DOLL
AR
^
      S')
```

```
      C1
*************     COMPACTION SUMMARY    *************

NUMBER OF COMPACTORS           =  1
IDEAL COMPACTION PRODUCTION =   642 CCY/HR
ACTUAL COMPACTION PRODUCTION=   545.540625 CCY/HR
NUMBER OF SPREADERS            =  1
IDEAL SPREADER PRODUCTION      =   750 CCY/HR
ACTUAL SPREADER PRODUCTION     =   637.5 CCY/HR
PROJECT TOTAL VOLUME           =     2600000 CCY
HOURLY COST                    =   107.92
/HR
TOTAL TIME NEEDED              =     4766.0 HOURS
    TIME FOR COMPACT.          =     4766.0 HOURS
    TIME FOR SPREAD.           =     4078.4 HOURS
TOTAL PROJECT COST             =   514346.72 DOLLARS
                  COST SUMMARY

COMPACTION UNIT COST      =    .11
/CCY
SPREADER UNIT COST        =    .09
/CCY
```

```
        DRILLBLAST
ENTER BOREHOLE DIAMETER (INCHES) : .6
ENTER BURDEN RATIO (RECOMMENDED RB=30 RANGE 20<RB<40) : .30
ENTER SPACING RATIO (RECOMMENDED RS=1  RANGE 1<RS<2) : .1
ENTER DEPTH RATIO (RECOMMENDED RD=2.6  RANGE 1.5<RD<4.0) : .2.6
ENTER SUBDRILLING RATIO (RECOMMEND RJ=.35  RANGE .2<RJ<.5) : ..35
ENTER STEMMING RATIO (RECOMMEND RT=.9  RANGE .5<RT<1.3) : ..9
***NOTE ABOUT EXCAVATION LIFTS***
IF MULTIPLE LIFTS  ARE DESIRED
ENTER HEIGHT OF EACH FACE CUT'S) : .18
ENTER LENGTH + WIDTH OF AREA TO BE DRILLED/BLASTED (FEET) : .1325 1330

CALCULATED VALUES :
       (1)  BURDEN  = 15.00 FEET
       (2)  SPACING = 15.00 FEET

ENTER LINE NUMBER TO CHANGE DATA
      OR HIT RETURN TO CONTINUE:   .

                  BENCH GEOMETRY SUMMARY

BURDEN =15.00 FEET.
SPACING=15.00 FEET.

LIFT                          1      TOTAL
FACE CUT HEIGHT     =       18.0      18.0
DRILL DEPTH         =       21.0      21.0
SUBDRILLING         =        3.0       3.0
STEMMING            =       13.5      13.5
HGT. POWDER COLUMN  =        7.5       7.5
BCY/LIFT            =    1174833   1174833
```

```
ENTER EXPLOSIVE LOADING DENSITY (LB/FT) : .6.8
ENTER PRIMER WEIGHT (LB/HOLE) : .2.5

CALCULATED VALUE (FOR EACH LIFT):
POWDER FACTOR = 0.32 *** OUTSIDE RANGE ***

CHANGE BURDEN OR SPACING?  (TYPE YES OR HIT RETURN)   .N
WHAT?
CHANGE BURDEN OR SPACING?  (TYPE YES OR HIT RETURN)   .
CHANGE BENCH GEOMETRY/ASHS PARAMETERS?  (TYPE YES OR HIT RETURN) .

ENTER OVERDRILLING FACTOR (IE: 10 PERCENT= 10 ) : .10

LIFT                          1       TOTAL
NUMBER OF HOLES     =      8616       8616
LENGTH OF DRILLING  =    180925     180925   FEET

ENTER NUM WEEKS, DAYS/WEEK, HOURS/DAY AVAIL FOR DRILLING : .52 6 9
ENTER EXPECTED DRILLING RATE (LF/HOUR/DRILL) : .40

PROJECT REQUIRES             1.61 DRILLS/LIFT
FLEET DRILL RATE    =          64 LF/HOUR/LIFT
ESTIMATED DURATION  =        2808 HOURS/LIFT      2808 HOURS TOTAL
ENTER NUMBER OF DRILLS TO BE USED(PER LIFT) : .8

ENTER TOTAL NUMBER OF WORKERS REQUIRED FOR DRILLING OPERATION
     *** PLACE NUMBER BELOW EACH TYPE ***
         FOREMEN COMPRESSOR  DRILL        HELPERS
                 OPERATORS   OPERATORS
ENTER   : .2      2            8            4
     ENTER CORRESPONDING WAGE BELOW EACH WORKER
           FOREMEN COMPRESSOR  DRILL        HELPERS
                   OPERATORS   OPERATORS
ENTER /HR : .13.85     11.60       11.60       10.70
ENTER EQUIPMENT COST (/HR/UNIT) : .120
ENTER SUPPLY COSTS (/LF) : ..03
```

```
                    DRILLING COST SUMMARY

QUANTITY                  180925 LF                1174833 CY

LIFT                         1     TOTAL
NUMBER OF HOLES           8616      8616
NUMBER OF DRILLS             8
DURATION                   566       566

COST            /LF         TOTAL        /CY          TOTAL
LABOR.....      .583    105479.27       .090      105735.00
EQUIPMENT.     3.000    542775.00       .462      542773.00
SUPPLIES..      .030      5427.75       .005        5874.17
          ------------------------------------------------
TOTAL.....     3.613    653682.02       .557      654382.17

ENTER SALES TAX (IE: 6 PERCENT= 6) : .6
REQUIRED EXPLOSIVES = 417876 LBS
ENTER EXPLOSIVE PRICE, INCL. BASE PRICE + MARKINGS (/100LBS) : .26
REQUIRED PRIMER     = 21540 LBS
ENTER PRIMER PRICE, INCL. BASE PRICE + MARKINGS (/100LBS) : .73
ENTER NUMBER OF DELAY PERIODS : .4
NUMBER OF CAPS PER DELAY EQUALLY PROPORTIONED? (NO OR HIT RETURN) .
ENTER BLASTING CAP PRICE. INCL. BASE + ADD. CHARGES
DELAY:                     1       2       3       4
NUM. OF CAPS/DELAY=     2154    2154    2154    2154
ENTER /100 CAPS : .      130     130     130     130
STEMMING QUANTITY AUTOMATICALLY INCLUDES 25 PERCENT WASTE
ENTER STEMMING UNIT PRICE (/TON) : .4.75
ENTER LOADING DENSITY OF STEMMING MATERIAL (LB/CY) : .2800
```

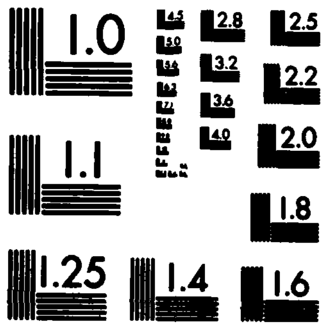
```
                    BLASTING MATERIAL COSTS
**************************************************************
                    TOTAL                 /LF              /CY
EXPLOSIVES..      115166.63.....        .637.....         .098
PRIMERS.....       16667.65.....        .092.....         .014
CAPS........       11872.85.....        .066.....         .010
STEMMING....        7453.21.. ..        .041.....         .006
TOTAL......       151160.33.. ..       .835.....         .129
**************************************************************

ENTER NUM OF WEEKS, DAYS/WEEK, HOURS/DAY USED FOR BLASTING : .20   5   2
ENTER BLASTING CREW LOADING RATE (LF/HR/CREW) : .75

PROJECT REQUIRES        12.06 CREW(S)/LIFT
ESTIMATED DURATION =     200 HOUR(S)/LIFT,    200HOURS TOTAL
ENTER NUMBER OF CREWS TO BE USED(PER LIFT) : .2

ENTER TOTAL NUMBER OF WORKERS REQUIRED FOR BLASTING OPERATION
     *** PLACE NUMBER BELOW EACH TYPE ***
        BLASTERS  LABORERS
ENTER B           : .2    4
          ENTER CORRESPONDING WAGE BELOW EACH WORKER
             BLASTERS LABORERS
ENTER /HR : .15.15     10.70
```

```
            SUMMARY OF DRILLING AND BLASTING COSTS
                                  DRILLING                 BLASTING
QUANTITY    ..............      180925 LF .........     1174833 CY
NUM OF DRILLS                        8 DRILLS/LIFT
NUM OF BLASTING CREWS                2 CREWS/LIFT
DURATION                           566 HOURS               1206 HOURS

UNIT COST
  LABOR     ..............        .583  .. ..........       .029
  SUP/MAT   ..............        .030  .............       .129
  EQUIPMENT ............         3.000  .............   --------
  TOTAL  ................        3.613  Z/LF  .......       .158 Z/CY

TOTAL COST     ....... Z 653682.02  ......... Z 185230.50

PROJECT UNIT COST ........      .714 /CY

SUPPLEMENTAL INFO:
BOREHOLE DIAMETER     =  6.00 INCHES
BURDEN                = 15.00 FEET
SPACING               = 15.00 FEET
POWDER FACTOR         =   .32 PER LIFT
LOADING DENSITY       =  6.80 LBS/FT

 **-END DRILLBLAST-**
```

CONSTRUCTION(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON
AFB OH F T UHLIK AUG 84 AFIT/CI/NR-84-58T

LASSIFIED F/G 13/2 NL

END
FILMED
DTIC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
7.1
8.0

```
     PROFILEPLOT
CURRENT STATION NUMBERS
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000
IS THE DATA ABOVE CORRECT? (YES/NO)  Y
CURRENT DENSITY DATA:
 BCY  LCY  CCY
 3300 2650 4000
 4700 3300 5200
IS THE ABOVE DATA CORRECT? (YES/NO)  Y
--------------------------------------------------------------
DO YOU HAVE VOLUMES ALREADY CALCULATED ? Y
ARE THE VOLUMES CALCULATED BY MATERIAL TYPE ? N
CURRENT VOLUMN DATA
 STATION   AND   STATION  FILL (CCY)  CUT (BCY)
         .0       1000.0          .0   378527.0
     1000.0       2000.0     11137.0   221603.0
     2000.0       3000.0     37289.0   143402.0
     3000.0       4000.0     34541.0   385020.0
     4000.0       5000.0     48300.0   634172.0
     5000.0       6000.0     16862.0   418548.0
     6000.0       7000.0    424362.0     1899.0
     7000.0       8000.0    558353.0    11229.0
     8000.0       9000.0    547682.0     9696.0
     9000.0      10000.0    224633.0    15017.0
    10000.0      11000.0    249030.0    45537.0
    11000.0      12000.0    270505.0    43521.0
    12000.0      13000.0    138117.0    98608.0
    13000.0      14000.0     47191.0   534493.0
IS THIS CORRECT? (YES/NO) Y
```

```
DO YOU WANT IT BROKEN DOWN BY TYPES ? (YES OR NO) Y
BELOW IS ELEVATION DATA
   STATION    PRESENT   PLANNED
        .0      594.0     531.0
    1000.0      553.0     505.0
    2000.0      520.0     523.0
    3000.0      565.0     542.0
    4000.0      552.0     560.0
    5000.0      605.0     554.0
    6000.0      478.0     512.0
    7000.0      425.0     468.0
    8000.0      339.0     421.0
    9000.0      336.0     375.0
   10000.0      299.0     325.0
   11000.0      220.0     275.0
   12000.0      214.0     225.0
   13000.0      184.0     175.0
   14000.0      142.0     110.0
IS THE ABOVE DATA CORRECT? (YES/NO) Y
BELOW IS THE CURRENT SUBSURFACE DATA
     STATION        GROUND       DEPTH1        DEPTH2
       400.0         5[illegible]9.0        20.0
       800.0         544.0         16.0
      4700.0         592.0         25.0
      5000.0         602.0         30.0
      5400.0         598.0         28.0
          .1         531.0         10.0
IS THE DATA CORRECT? (YES/NO) Y
DO YOU WANT A PLOT OF THE ELEVATION DATA? Y
     1 = TEKTRONIX 4662 PLOTTER
     2 = HDS CONCEPT APL TERMINAL (CRT)
     3 = NIETHER, ABORT REQUEST
ENTER ENTER THE TYPE OF PLOTTER/TERMINAL:  1
THE ENTIRE PROFILE GRAPH CAN BE COMPRESSED INTO ONE GRAPH
OR BROKEN INTO SEGMENTS
ENTER ENTER THE NUMBER OF PROFILE SEGMENTS DESIRED:  1
```

```
INSTRUCTIONS FOR PLOTTER
  1) TURN PLOTTER ON IF NOT ALREADY
  2) PRESS LOAD BUTTON DOWN
  3) PLACE PAPER ON PAD
  4) PRESS LOAD BUTTON DOWN SO IT POPS UP
  5) PRESS LOCAL KEY DOWN
  6) USE JOY STICK TO MOVE PIN TO UPPER RIGHT CORNER OF PAPER
  7) PRESS "SET UPPER RIGHT" BUTTON UNTIL THE BELL SOUNDS
  8) PRESS LOCAL BUTTON SO IT POPS UP
  9) TAKE THE COVER OFF THE PIN

WHEN THESE STEPS ARE COMPLETED

  PRESS THE RETURN KEY TO CONTINUE
```

VOLUME TABLE

STATION	EXCAVA. (BCY)	1ST LAYER (BCY)	2ND LAYER (BCY)	3RD LAYER (BCY)	EXCAVA. (CCY)	EMBANK. (CCY)
0						
	378527	245438	133089	0	322778	0
1000						
	221603	112110	109493	0	191456	11137
2000						
	143402	102395	41007	0	121540	37289
3000						
	385020	294770	90250	0	324757	34541
4000						
	634172	453934	180238	0	537403	48300
5000						
	418548	234313	184235	0	359828	16862
6000						
	1899	0	1899	0	1716	424362
7000						
	11229	0	11229	0	10149	558353
8000						
	9696	0	9696	0	8764	547682
9000						
	15017	0	15017	0	13573	224633
10000						
	45537	0	45537	0	41158	249030
11000						
	43521	0	43521	0	39336	270505
12000						
	98608	0	98608	0	89126	138117
13000						
	534493	0	534493	0	483099	47191
14000						
TOTAL	2941272	1442959	1498313	0	2544686	2608002

* *

NOTE: COLUMN 6 IS IN DIFFERENT UNITS THAN COLUMN 2

ELEVATIONS

STATION	EXISTING	PLANNED	1ST INTERFACE	2ND INTERFACE
.0	594.0	531.0	521.0	
.1	531.0	531.0	521.0	
400.0	529.0	520.6	509.0	
800.0	544.0	510.2	528.0	
1000.0	553.0	505.0	530.0	
2000.0	520.0	523.0	520.0	
3000.0	565.0	542.0	550.0	
4000.0	552.0	560.0	552.0	
4700.0	592.0	555.8	567.0	
5000.0	605.0	554.0	572.0	
5400.0	598.0	537.2	570.0	
6000.0	478.0	512.0	478.0	
7000.0	425.0	468.0	425.0	
8000.0	339.0	421.0	339.0	
9000.0	336.0	375.0	336.0	
10000.0	299.0	325.0	299.0	
11000.0	220.0	275.0	220.0	
12000.0	214.0	225.0	214.0	
13000.0	184.0	175.0	184.0	
14000.0	142.0	110.0	142.0	

DO YOU WANT A PLOT OF THE HAUL-MASS DIAGRAM? (YES/NO) Y
    1 = TEKTRONIX 4662 PLOTTER
    2 = HDS CONCEPT APL TERMINAL (CRT)
    3 = NONE OF THE ABOVE
ENTER WHICH TYPE OF PLOTTER/TERMINAL DO YOU HAVE?: 1

INSTRUCTIONS FOR PLOTTER

1) TURN PLOTTER ON IF NOT ALREADY
2) PRESS LOAD BUTTON DOWN
3) PLACE PAPER ON PAD
4) PRESS LOAD BUTTON DOWN SO IT POPS UP
5) PRESS LOCAL KEY DOWN
6) USE JOY STICK TO MOVE PIN TO UPPER RIGHT CORNER OF PAPER
7) PRESS "SET UPPER RIGHT" BUTTON UNTIL THE BELL SOUNDS
8) PRESS LOCAL BUTTON SO IT POPS UP
9) TAKE THE COVER OFF THE PIN

WHEN THESE STEPS ARE COMPLETED

PRESS THE RETURN KEY TO CONTINUE

HAUL-MASS DIAGRAM ORDINATES

STATION (FEET)	CUMMULATIVE VOLUME (CCY)
0	0
1000	322778
2000	503097
3000	587348
4000	877554
5000	1366667
6000	1709634
7000	1286988
8000	738784
9000	199866
10000	¯11194
11000	¯219066
12000	¯450234
13000	¯499225
14000	¯63316

STATION	EXCAVATION (LCY) TOP LAYER	2ND LAYER	3RD LAYER	TOTAL
0 – 1000	305640	189551	0	495191
1000 – 2000	139609	155944	0	295553
2000 – 3000	127510	58404	0	185915
3000 – 4000	367072	128538	0	495610
4000 – 5000	565276	256703	0	821979
5000 – 6000	291786	262395	0	554181
6000 – 7000	0	2705	0	2705
7000 – 8000	0	15993	0	15993
8000 – 9000	0	13809	0	13809
9000 – 10000	0	21388	0	21388
10000 – 11000	0	64856	0	64856
11000 – 12000	0	61984	0	61984
12000 – 13000	0	140442	0	140442
13000 – 14000	0	761248	0	761248
TOTAL	1796893	2133960	0	3930853

*** END OF PROFILEPLOT ***

VITA

Felix T. Uhlik III was born on January 9, 1949 in Kearny, New Jersey. He attended Catholic schools in Elmwood Park and Fair Lawn, New Jersey and graduated from Fair Lawn Senior High School in 1966. Mr. Uhlik graduated from New Jersey Institute of Technology (then Newark College of Engineering) in 1970 with a B.S. in Civil Engineering. He received his M.S. in Civil Engineering in 1974 from the Air Force Institute of Technology.

He entered the Air Force in 1970 through the Reserve Officer Training Corps (ROTC) program and has had assignments in Mississippi, California, Missouri, Ohio, Thailand, Nebraska, and Colorado. Mr. Uhlik is currently a Major in the United States Air Force and will be returning to the United States Air Force Academy as an Associate Professor in the Civil Engineering Department.

In 1970 he married Nancy Segalla of Paterson, New Jersey and they have two sons, Brian and Mark.

END

FILMED

10-84

DTIC