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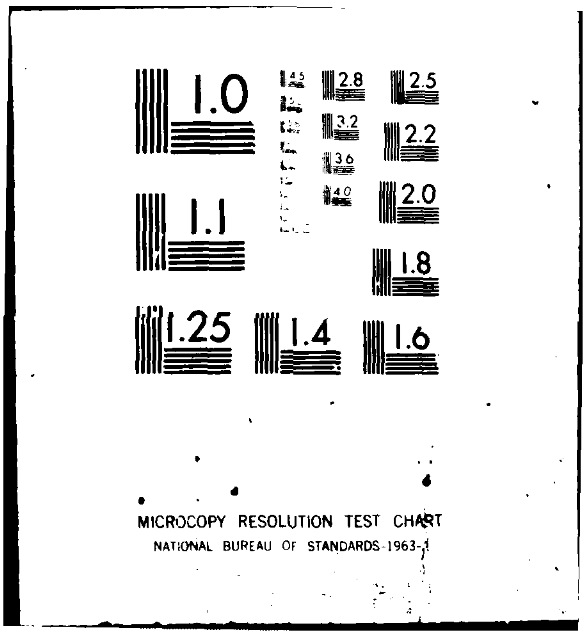
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PROBABILISTIC SOIL SAMPLING PROGRAM FOR MX-RELATED SITE CHARACTERIZATION

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by

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The report outlines a methodology for characterizing the variability of geotechnical parameters within large areas with complex geology and for designing sampling and testing programs which maximize the probabilistic information that can be obtained within specified constraints on program time and cost. The methodology is focused on the problem of characterizing near-surface compressibility in alluvial valleys of the Basin and Range physiographic province. To illustrate the methodology, a specific sampling plan (Continued)

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20. ABSTRACT (Continued)

is designed for Ralston Valley, Nevada, aimed at defining the valley-wide variation in uniaxial strain (UX) compressibility to a depth of 160 feet, and providing information about the vertical and horizontal correlation structure and frequency content of this spatial variation. The plan is also designed to permit determining if statistically significant correlations exist between UX compressibility and more readily measured parameters, such as surficial geologic unit designations, seismic P-wave velocities, soil classifications and gradation curves, and in situ composition information (dry density, porosity, etc.).

PREFACE

This report was prepared by Dr. Erik H. Vanmarcke, Professor of Civil Engineering at the Massachusetts Institute of Technology (MIT), as part of work being performed at the U. S. Army Engineer Waterways Experiment Station (WES) in support of Task V-1, "Site Characterization and Material Properties," of the Air Force Ballistic Missile Office's Nuclear Hardness and Survivability Program for the MX missile system. WES funding was provided by the Defense Nuclear Agency under Subtask H53BAXSX377, Work Unit 28; Dr. Vanmarcke was subsequently funded by WES via Purchase Order No. DACA39-79-M-0068.

Dr. J. G. Jackson, Jr., Geomechanics Division (GD), Structures Laboratory (SL), was the WES Contracting Officer's Representative; technical assistance was provided by Messrs. A. E. Jackson, Jr., and B. R. Phillips, GD.

Mr. Bryant Mather was Chief of SL during the preparation of this report. The Commander and Director of WES was COL Nelson P. Conover, CE, and the Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, INCH-POUND TO
METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.6093	kilometres
square miles	2.590	square kilometres

PROBABILISTIC SOIL SAMPLING PROGRAM FOR MX-RELATED SITE CHARACTERIZATION

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Air Force's proposed MX missile system will most likely be deployed within the alluvial valleys of the Basin and Range physiographic province of the western United States (Ref. 1). Several regions, each containing 6000 to 7000 square miles of "suitable" area, have been identified as potential sites. The region of primary interest at present is the Nevada-Utah study area, which consists of 30 Candidate Deployment Parcels (CDPs) or "valleys". Under contract to the Air Force Ballistic Missile Office (BMO), Fugro National, Inc., is performing generalized geotechnical investigations of these valleys, with primary emphasis on the construction aspects of various basing options (Ref. 2). The Defense Nuclear Agency (DNA) has funded the U. S. Army Engineer Waterways Experiment Station (WES) to conduct specialized site characterization and soil property investigations to support BMO's Nuclear Hardness and Survivability (NH&S) Program.

The basing concepts for the MX system essentially consist of probabilistic "shell games" in which a relatively small number of missiles are concealed within a much larger number of hardened shelters. If the nuclear ground shock calculations used in shelter vulnerability analyses are to be consistent with this scenario, it is necessary that the soil profiles and properties used as input be probabilistically quantified. But the area to be covered is simply too large and the available time too short to accomplish this by a "brute force" sampling and testing program. A much more efficient approach is needed. Experience and published data suggest that soil deposits that result from similar geologic processes and that have similar composition will have similar engineering properties (Ref. 3). Thus it seems reasonable to approach the problem by probabilistically characterizing the variability of key ground shock-relevant geotechnical properties within a single valley and then statistically correlating the results with more readily measured parameters such as those being evaluated by Fugro for all 30 valleys.

For ground shock assessments, the most relevant geologic measurement is the depth to the first major reflector, as determined by a seismic refraction survey; the most relevant soil property is the volume compressibility of the materials above this reflector, as determined by uniaxial strain (UX) tests on undisturbed specimens. Should a statistically meaningful correlation exist between UX compressibility and surficial geology, then Fugro's valley-wide maps of surficial geologic units would be extremely useful for NH&S studies. The map for Ralston Valley is shown in Figure 1.1; geologic unit symbols are defined in Table 1.1. Other potentially useful Fugro data are their seismic P-wave velocity measurements, soil classifications and gradation curves, and in situ composition information such as dry density and porosity.

1.2 PURPOSE AND SCOPE

The purpose of this report is to outline a methodology for characterizing the variability of geotechnical parameters within large areas with complex geology and for designing sampling and testing programs which optimize the probabilistic information that can be obtained within specified cost and/or time constraints. The methodology is focused on the problem of characterizing near-surface compressibility within a typical alluvial valley in the Basin and Range physiographic province. To illustrate the methodology, a specific sampling plan is developed for defining compressibility variation within a single stratum of a single valley (i.e., the 0- to 20-foot stratum of Ralston Valley, Nevada) under a WES-prescribed set of sampling type, cost and time constraints.

The various factors to be considered in developing a probabilistic soil sampling plan are outlined in Chapter 2; a more detailed discussion of the basic concepts involved in stochastic site characterization is given in Refs. 4 and 5. Development of an optimization methodology and a recommended sampling plan for Ralston Valley is presented in Chapter 3. Field implementation of the plan, including additions made to extend the characterization to a depth of 160 feet and obtain parallel seismic refraction measurements, is described in a brief epilogue.

Table 1.1 Geologic Units for MX Soils (from Ref. 2)

Symbol	Description
Au	Non-rock Deposits (undifferentiated); fine- to coarse-grained materials deposited by alluvial, fluvial, eolian, lacustrine, gravity or glacial processes.
A1	Fluvial Deposits; predominantly composed of poorly to well-graded sand and gravel with lesser amounts of silt- and boulder-sized material. The unit predominantly consists of recent water-laid deposits occupying present drainages and floodplains.
	-Older Fluvial Deposits (A1o) are generally thicker, more extensive units deposited in ancestral fluvial systems.
	-Alluvial Outwash Deposits (A1w) consist of mixed, geomorphically nondescript alluvial and fluvial deposits covering large, relatively flat, river and playa basins.
A2	Terrace Deposits; predominantly composed of moderately to well-graded, clay- to gravel-sized material. Principally elevated terraces bordering modern streams (A2s) and lakes/playas (A2l).
A3	Eolian Deposits; predominantly composed of poorly graded sand-sized material deposited by wind action. Deposits may consist of mixed sand, silt, and clay (A3u), or be differentiated on the basis of predominant grain size and landform.
	A3s/d - Predominantly fine sand-sized material deposited in sheets (A3s) or dunes (A3d).
	A3l - Loess composed predominantly of silt-sized material with lesser amounts of clay and fine sand.
	A3f - Predominantly clay-sized material with lesser amounts of silt and fine sand.
A4	Lacustrine, Estuarine, and Playa Deposits; predominantly composed of poorly graded clay, silt, and fine sand deposited in bodies of standing water. Older lacustrine, estuarine, and playa deposits (A4o) are thicker, more extensive units occupying ancestral lake basins.
A5	Alluvial Fan Deposits; predominantly composed of well-graded sand and gravel with varying amounts of silt-, cobble-, and boulder-sized material. Deposited principally by distributary channels adjacent to mountain fronts. Relative ages are indicated by o - older, i - intermediate, or y - younger.
A6	Pediment, Pediment Deposits, and Areas of Shallow Rock; planated bedrock shelf or near-surface rock generally overlain by a thin mantle of sand- to boulder-sized residual or alluvial material.
A7	Colluvial Deposits; predominantly composed of moderately to well-graded sand and gravel with varying amounts of silt-, cobble-, and boulder-sized material. Deposited locally by gravity and water adjacent to steep gradients.

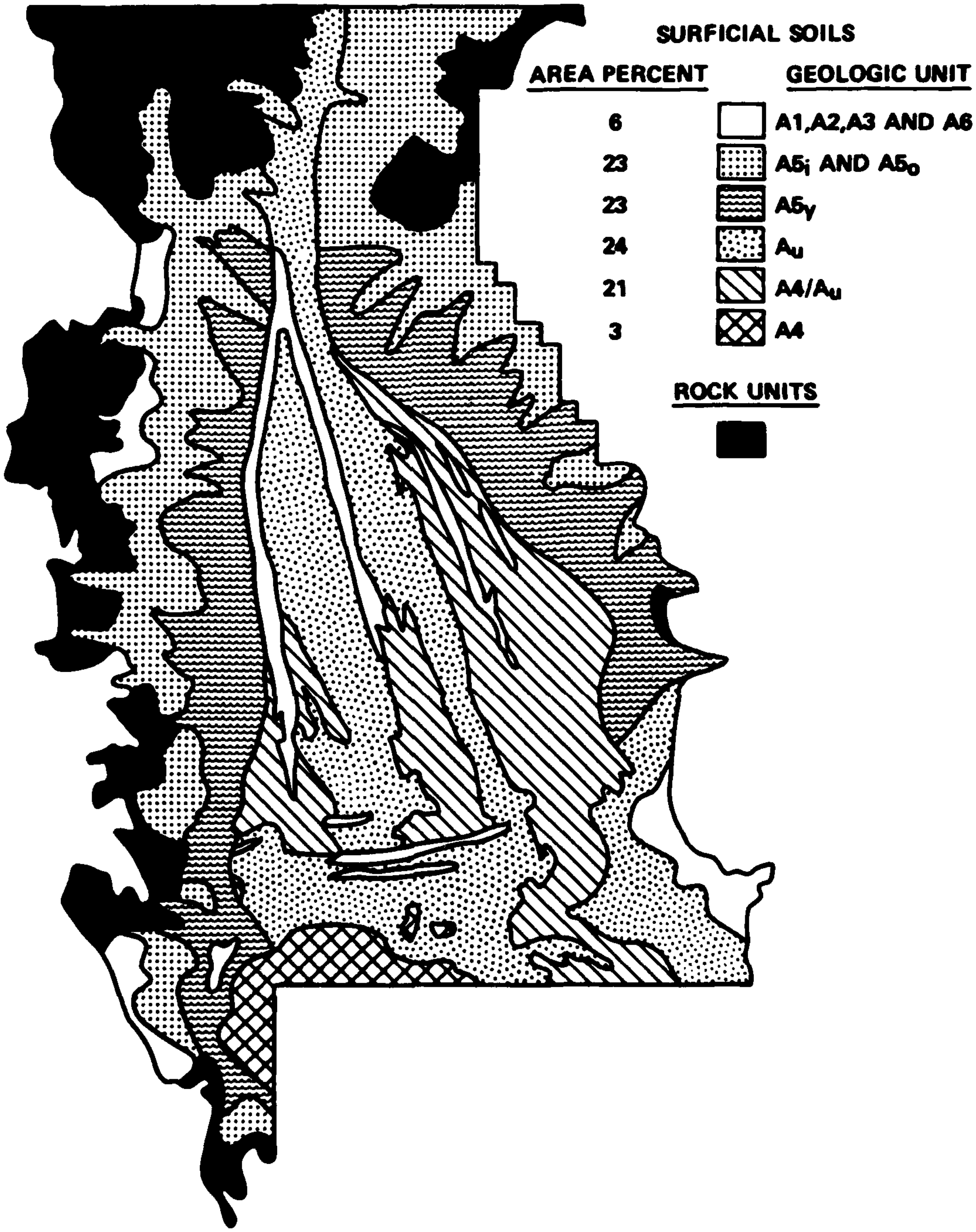

Figure 1.1 Geologic map of surficial soils for Ralston Valley, Nevada (from Ref. 2).

CHAPTER 2

PROBABILISTIC SITE CHARACTERIZATION

2.1 GENERAL

Probabilistic site characterization serves a dual function: (a) it provides a format for quantifying engineering information (acquired during site investigation, sampling and testing) about soil profiles and properties at a site, and (b) it provides the basis for predicting load effects on structures in probabilistic terms, i.e., for quantifying the variability and the reliability of load effect predictions. A probabilistic description of a soil profile formalizes the all-important (but poorly understood) connection between the amount and the quality of exploration and testing at a site on the one hand, and the quality of the resulting performance predictions on the other hand. Through this connection, criteria imposed on the quality of the "end product" (specifically performance predictions or design) can be translated, in principle, into requirements for the site investigation effort (Ref. 4).

Site characterization and associated predictions of structural performance are of course not "static". They may be updated from time to time during a project, when new information becomes available. Probability theory provides a mathematical procedure, in the form of Bayes Theorem, for updating prior assessments of site conditions and probable performance when new information becomes available. It may be argued that planning and executing the process of updating performance predictions in essence formalizes Terzaghi's "observational approach".

Uncertainty about the properties of soil deposits is primarily of the passive type. A soil property at a given point in a soil mass is deterministic; however, the value is unknown until accurately measured. Moreover, it is understood that a particular soil property is likely to vary from point to point even within nominally homogeneous deposits. Changes also occur with time under the influence of loads, the flow of water, chemical processes, etc.

Probability theory can be used to quantify our state of information (or lack of information) about a soil profile characteristic. Probability statements either reflect the engineer's judgement (degree of belief) about subsurface conditions, or constitute a statement about the relative frequency of occurrence of particular soil types or soil properties within a given volume of soil. These subjective and objective interpretations of probability complement each other.

Uncertainty about soil properties and soil behavior leads to differences between actual and predicted performance. Extremes of a soil property may be much farther removed from (or closer to) the mean than is assumed in analysis and design. These errors eventually lead either to losses attributable to inadequate performance or failure (structure underdesigned) or to expenditures in excess of those really needed (structure overdesigned). A realistic assessment of the variability of site profiles and properties would permit fine-tuning the design so that these added expenditures can be controlled and minimized.

2.2 DECISIONS ABOUT SOIL SAMPLING AND TESTING

No complete systematic methodology has yet been developed that formalizes the process of decision-making about site exploration, sampling and testing, although many of the elements of a rational methodology are available at present. Probability analysis is an important ingredient of such a methodology because in principle it permits engineers to quantify uncertainty as well as the gain in information (decrease in uncertainty) that might result from a program of geotechnical data acquisition.

Spatial data acquisition networks are common in many other fields (e.g., hydrology, meteorology). The network designer must select recording station locations and must decide the type(s) of measurements to be taken at each station. The basic premise underlying the design of the network is that the attribute(s) of interest varies (vary) more or less randomly as a function of one or more spatial coordinates. Variation of the attribute with time may also be significant. The idea is that the attribute is observed only at discrete points in space and time. The network should be designed in such a manner that it should incorporate the possibility of characterizing attributes of interest at any point (sampled or not) in the most efficient manner, i.e., at the least cost per unit of supplementary accuracy achieved.

The costs to be minimized include the sampling/testing cost and also the expected opportunity loss, i.e., the difference between the expected net returns of a project designed on the basis of a higher level of accuracy and the cost of additional sampling and testing. The flow chart in Figure 2.1 depicts the decision situation.

2.3 SOURCES OF UNCERTAINTY

Two major sources of variability are recognized in the analysis. Each comprises a number of components. First, there is in situ or inherent variation; an attribute of interest is assumed to vary from location to location. We consider specifically the average vertical compressibility within a soil column extending to a given depth below the surface. If this quantity could be measured without error at many locations, a relative frequency function (a histogram) similar to that shown in Figure 2.2 could be constructed. Within a smaller area, it is likely that the variation will be characterized by a narrower histogram. Also, observations from areas characterized by the same surficial geological designation (Au, A5y, etc.) may have narrower histograms centered around different mean values, as shown in Figure 2.3.

Within a nominally homogeneous area, if the value of the attribute were to be plotted as a function of a spatial coordinate, some pattern of variation or fluctuation would emerge. The pattern of this fluctuation is of considerable interest in planning data acquisition programs. In some deposits, the attribute might vary slowly with distance; this variation is then seen either as a "trend" or as part of a (random) fluctuation with relatively long apparent wavelength. In other deposits, the mean value of the attribute might remain more or less constant, but there may be rapid and strong fluctuations about the mean. These two cases are illustrated in Figure 2.4. (The histogram characterizing the entire "population" might well be the same in both cases while the patterns of fluctuations would be very different.) It is important to learn more about the character of the in situ or inherent variation in the different types of deposits. More details and theoretical background about modeling of inherent variation of soil properties and profiles are provided in Refs. 4 and 5.

The second source of uncertainty is associated with measurement of the attribute. It too consists of a number of components, including errors due to sample disturbance and testing. One of the components relates to the fact that the attribute of interest is a spatial average involving a soil column (of given length, say 20 feet) from which only a fraction is actually tested.

Suppose that m specimens (from depths Δz, $2\Delta z$, ..., $m\Delta z$ within the 20-foot soil column) are tested, and that the soil column compressibility is estimated by averaging the specimen compressibilities. (Unequal weights could be used in the averaging procedure, to reflect the relative importance of the compressibility at various depths in the displacement calculation.) Assuming that there are no testing or measurement errors in determining specimen compressibility, the error in estimating the soil column compressibility will decrease as m increases. (This error component can in principle be eliminated by testing the entire soil column.) Random testing and measurement errors in the determination of specimen compressibilities can also be reduced by increasing the number of samples (m) per boring location. Systematic measurement errors can only be quantified by comparing and calibrating methods of sampling and testing.

2.4 TYPES OF GEOTECHNICAL DATA ACQUISITION PROGRAMS

It is useful to categorize geotechnical data acquisition programs according to the type or level of information they are designed to generate. The objective of the program under study is to provide baseline information about the sources of uncertainty in near-surface compressibility, and about the amount of uncertainty contributed by each source. It is expected that much of the information generated will be transferable to similar geological settings (i.e., other valleys in the Basin and Range province). This program will also generate background information that can be used to design "higher level" geotechnical data acquisition programs in a more informed, rational manner.

The basic objective of any site exploration and testing program is to reduce uncertainty. However, in a baseline data acquisition effort, the objective may be more aptly stated: try to eliminate confusion or ignorance about uncertainty by identifying the sources of uncertainty and quantifying the degree of uncertainty associated with each source. Once the degree of uncertainty is known, appropriate conservatism can be introduced in design by informed, rational selection of safety factors, or one may decide that more information is needed to reduce the uncertainty. Lack of knowledge about variability is expensive because it tends to lead either to overdesign or to lack of sufficient protection.

Once the sources and levels of uncertainty have been assessed, it then becomes meaningful to consider steps that can be taken to improve the prevailing state of uncertainty. In considering the effectiveness of such steps (taken as part of a "higher level" data acquisition program), the engineer must consider subsequent decisions in siting, design and construction. If a single design is to be used for all structures within a given area, it would be wasteful to try to define the actual patterns of variation of a soil property that affects response and performance. It probably suffices to define the relative frequency of occurrence of the property within the area of interest. By contrast, if designs will be permitted to differ from location to location, then information about the specific pattern of variation of a pertinent soil property becomes useful.

Data acquisition programs can be carried out in a "sequential" or in a "simultaneous" mode. In a sequential program, data gathering occurs in stages; after each stage, the information is processed before working out the details of the next stage of the program. This report is primarily concerned with "simultaneous" data acquisition; it is assumed that decisions about boring locations throughout the valley, sample depths and types, and the lab testing plan are all made before drilling starts. It may be noted, however, that the methodology applicable to simultaneous program planning can also be used to analyze one state (any state) of a sequential program.

2.5 CONSIDERATIONS IN SAMPLING PLAN DESIGN

2.5.1 Statistical Sampling Patterns

In the statistics literature, frequent reference is made to the following types and patterns of sampling in space:

(a) Random sampling: Selection process that gives each location an equal chance of being sampled; requires the use of a table of random numbers to select boring locations; assumes that observations at different locations are uncorrelated.

(b) Systematic sampling: Sampling on a grid or at equidistant points; method considered acceptable if there is no periodicity, i.e., if the variation of the attribute is not related to the selection criterion.

(c) Cluster sampling: Sampling of specimens in closely spaced groups, usually to decrease sampling cost; appropriate when the attribute sampled may be assumed to be unrelated to selection criteria; assumes lack of correlation among observations.

(d) Quota sampling: In quota sampling, one decides that there are several characteristics or factors which are closely connected to the attribute of interest, and one constructs the sampling pattern to make the selected locations representative with respect to these factors.

(e) Multistage Sampling: The general idea is first to sample among large (areal) units that comprise the total area of interest, then to sample within the selected units at a lower level, and so on. Every elementary surface unit has an equal chance of being selected. One must make sure that various subgroups are represented in a balanced way, e.g., proportional to the fraction of the total area occupied.

2.5.2 Engineering Considerations

To complement the statistician's perspective, the following geotechnical engineering factors may be considered in formulating a soil sampling plan:

(a) Relative importance in engineering analysis. For example, accurate determination of soil compressibility of top layers is more important than that of deeper layers.

(b) Influence of "loss function": Errors on the unconservative side are more costly than those on the safe side; it is appropriate to get more information about the weakest soil since its properties may control design. (But at the same time, one must make sure that enough information will be left in case the area with the weakest soil is excluded from siting consideration.)

(c) Consideration of time effects: One may choose fewer samples from locations more susceptible to unpredictable changes caused by environmental or construction-related factors since there is less value to each measurement.

(d) Location of structures: Density of borings should be concentrated in areas where facilities are likely to be located.

(e) Ease of access and proximity of roads.

Many of the statistical and geotechnical considerations just mentioned have been incorporated in the sampling plan design outlined in the next chapter.

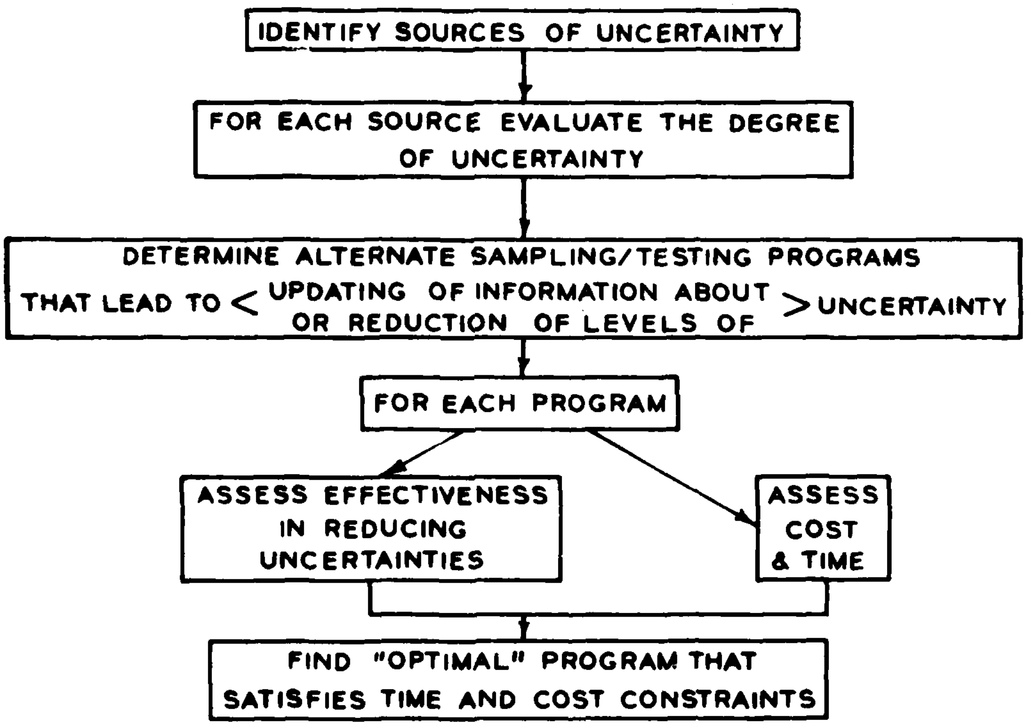

Figure 2.1 Decision flow chart for optimizing soil sampling/testing programs.

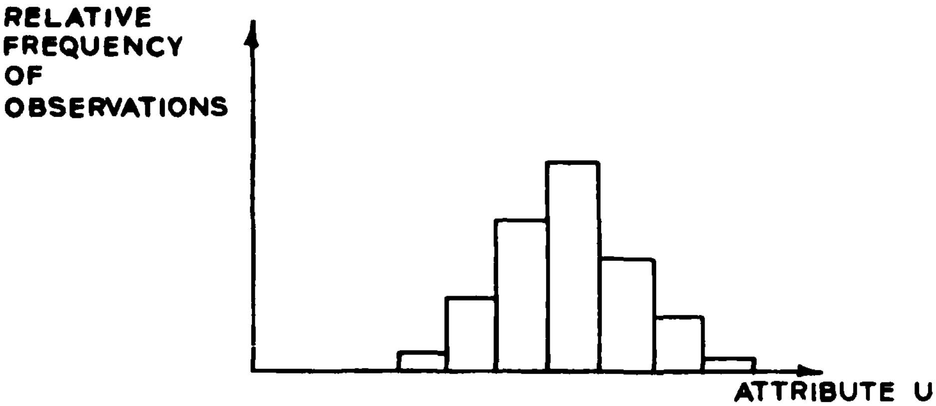

Figure 2.2 Histogram for variation of u within large area.

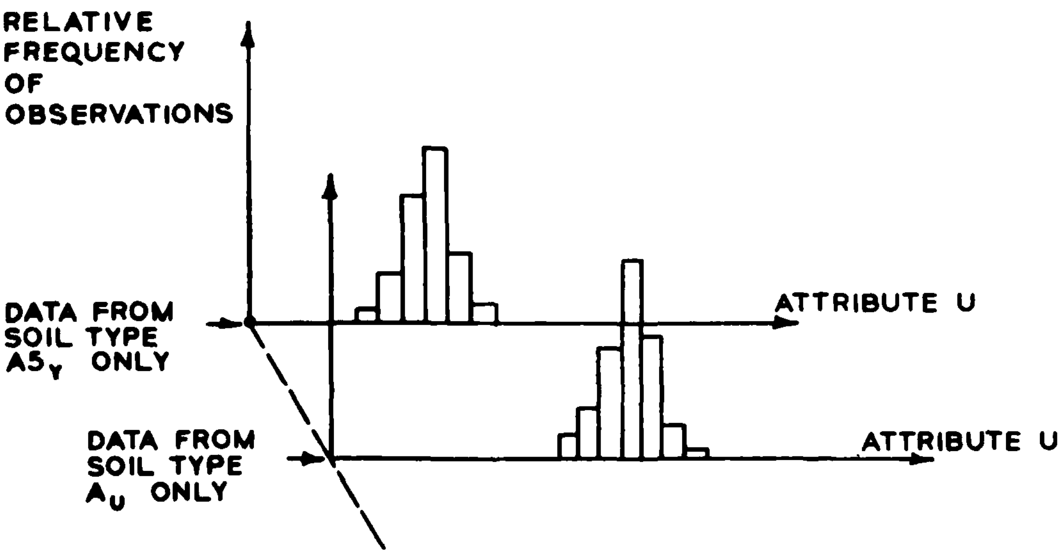

Figure 2.3 Histograms for variation of u within portions of large area.

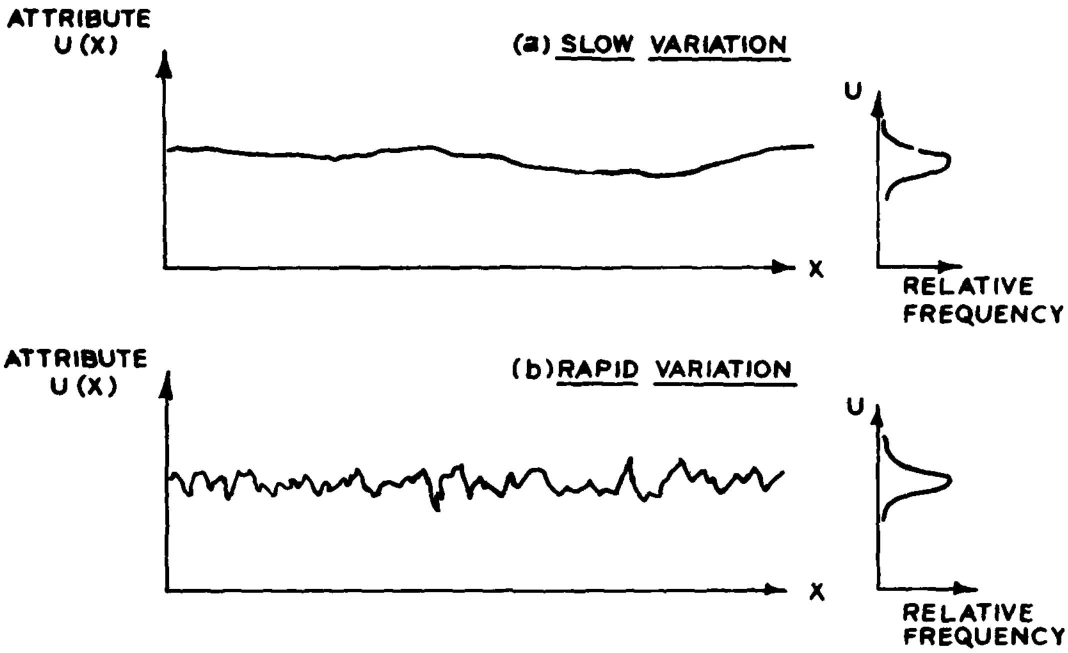

Figure 2.4 Slow and rapid spatial fluctuations of u for deposits having the same histograms.

CHAPTER 3

SAMPLING PLAN DESIGN

3.1 SCOPE AND OBJECTIVES OF METHODOLOGY

It must be stated at the outset that the general optimization problem for baseline geotechnical data acquisition cannot be formulated, much less solved, in an exact or unique way. Sampling and testing programs usually serve diverse and ill-defined objectives, and the constraints of time, money and manpower often cannot be spelled out clearly in advance. Thus, while overall optimization (w.r.t. all error sources and sampling purposes) may be the ideal, a less ambitious and more practical goal is to allocate the budget within the frame of each activity in a near-optimal manner, and to choose a satisfactory (hopefully near-optimal) mix of sampling activities.

The long-range focus of the analysis of alternative sampling plans is on the variance of the attribute at an arbitrary point in the space to be sampled (the "point" variance). The term "prior" variance is used to characterize the uncertainty about the attribute before the sampling and testing effort. The "posterior" variance characterizes the uncertainty remaining after the program is completed. In program planning and design, we seek to minimize the posterior variance of the attribute at all points of interest (i.e., at all points of the nonexcluded surface area of the alluvial valley under study; exclusions are based on property rights, excessive slopes, presence of rock or groundwater at shallow depth, etc.).

It has been suggested in Section 2.3 that the point variance of a soil property consists of a number of components (slow and rapid inherent fluctuations, random and systematic measurement errors). Until a baseline data acquisition program is carried out, the size of the variance components is essentially unknown. The very purpose of the baseline data acquisition program is to build a base of factual information about the variability of the attribute under study. This in itself constitutes a task of variance reduction (reduction of uncertainty about the variance), but one that is difficult to quantify. This is one of the reasons why the optimization problem defies exact solution: it must of necessity depend on poor information about prior variances and about the relative importance of the different components of the prior variance. In the absence of better information, it is reasonable to balance the level of effort devoted to the different tasks aimed at defining and ultimately reducing the different components of the variance.

Regardless of the "level" of the data acquisition effort, variance reduction is accomplished by increasing the quantity of data (i.e., the number of borings, samples, or tests) gathered as part of a particular program task. The optimization strategy developed herein is based on this observation. A number of tasks serving particular sampling purposes are identified in the following section. For those tasks and purposes judged equally significant in terms of impact on the overall variance, the size of the data base should be the same. The specific objective of the optimization effort is to <u>maximize the size of the data base</u> (i.e., maximize the number of borings) available for each sampling purpose, subject to the constraints of time and money.

It is natural to break down each major task into work units, e.g., individual borings or patterns of borings. Within the context of each sampling purpose, it is meaningful to consider the questions: "What is the 'optimum' spatial location of work units?" and "How do the sampling cost and time and the value of information gained depend upon the number of work units?" Answers to these questions, pursued in the next few sections, will permit suboptimization of the sampling plan within the context of each sampling purpose.

3.2 SPECIFIC SAMPLING PURPOSES

As stated before, the program serves in large part to generate baseline information about the degree of uncertainty attributable to the different variance components in the different locations of interest. Specifically, the program is designed to yield the following (interrelated) items of information:

(a) the histogram of near-surface compressibility in Ralston Valley (and its characteristics: mean, variance)

(b) the contribution from each "source of error" to the total uncertainty (inherent variability, random and systematic error components)

(c) identification of factors that permit narrowing the histogram (decreasing the variance) of near-surface compressibility (and hence, that are useful in predicting compressibility). The factors to be investigated are:

  (1) distance from mountains and/or centerline of valley
  (2) surface elevation

(3) surficial geologic unit designation
(4) seismic refraction P-wave velocity
(5) soil classification and gradation characteristics
(6) in situ density, porosity, etc.

(d) information about the correlation structure and the frequency content of the vertical and horizontal components of the spatial variation of compressibility and related index properties.

To obtain the information listed above, the following four specific <u>sampling purposes</u> are considered feasible:

(a) Sampling at different locations to determine histograms of near-surface compressibility:

(1) for the entire valley
(2) as a function of deposition travel distance (center of valley vs. near the mountain slopes) or surface elevation
(3) for areas with a given surficial geologic unit designation

(Average, variance and histogram can be estimated by data; estimated variance will reflect the influence of all components except <u>systematic</u> measurement errors.)

(b) Sampling at different depths within a boring to determine <u>vertical</u> variation and correlation characteristics (only inherent or in situ variation is of interest here, but scatter in data will also reflect random measurement errors.)

(c) Sampling to determine <u>horizontal</u> variation and correlation characteristics. (Only inherent or in situ variation is of interest, but scatter in data will also reflect random measurement errors.)

(d) Sampling within a closely spaced group of borings to determine variation "at a point." (Average and variance can be estimated from the data; estimated variance will represent random measurement error and irreducible small-scale inherent or in situ variation.)

3.3 CONSTRAINTS ON TYPE, COST AND TIME OF SAMPLING

Based on discussions with WES, the following constraints on type, cost and time of sampling were assumed. All undisturbed samples are to be extracted from 5-inch-diameter by 2.5-foot-long steel Shelby tubes; all borings are to be drilled dry, using either compressed air or foam as the drilling fluid. Borings can be either of two types, as shown in Figure 3.1 and described below:

Type A: 20-foot-deep continuous sample; provides eight undisturbed samples.

Type B: 20-foot-deep single sample boring; provides one undisturbed sample from the 10-foot depth plus several bag samples.

The time to move and reinstall the drilling equipment is about 2 hours unless the distance between locations exceeds 5 miles (8 km). The cost for a Type A boring is about $1200 and the drilling time required is one day. The daily cost for a Type B boring is about $1100. Five Type B borings can be drilled in one day if the drilling equipment remains stationary (e.g., swinging of drill rig to sample "at a point"); three Type B borings can be drilled in one day if the drilling equipment has to be moved over distances not exceeding about 5 miles (8 km).

Overall time and budget constraints were also imposed. The total cost of the sampling program is to be less than C = $60,000 and the time limit on the job, dictated by the availability of the drilling crew and equipment, is T = 55 days.

3.4 BORING PATTERNS FOR DIFFERENT SAMPLING PURPOSES

The sampling purposes (1 through 4) will now be discussed in more detail. The aim is to rationalize the choice of boring locations within the framework of each sampling purpose.

3.4.1 Sampling Purpose 1

The key requirement is that representative boring locations and samples be obtained. Since several different soil types (identified by the different surficial deposit designations) are possible, adequate sampling within each soil type is necessary. Location with respect to the valley center and the mountain slopes should also be considered in selecting boring locations within each soil type.

There exist simultaneously the need to space borings widely in order to minimize correlation and enhance representativeness, and the desire to cluster them in order to save expenses and drilling rig relocation time. A compromise may be reached by locating clusters of borings at widely different locations within the area covered by each soil type. Within each cluster, borings should be sufficiently far apart (about 500 feet or more) to minimize spatial correlation effects.

The choice of specific locations within the area covered by a given surficial soil type is largely dictated by considerations of cost and time of sampling, e.g., the choice of roadside locations as well as some degree of spatially clustered sampling to save relocation time. Of course, if specific shelter locations were known in advance, one might concentrate the sampling effort in those locations.

3.4.2 Sampling Purposes 2 and 3

Spatial correlation significantly influences the effectiveness of any geotechnical data acquisition effort. For Sampling Purpose 1, boring locations should be sufficiently far apart to avoid wasting resources due to partial duplication of measurements. But correlation is beneficial when information transfer from one location to another is desired. If the spatial correlation is low, information transfer is difficult, and it implies that a high density of sampling in space is required to establish the actual pattern of variation of a property or profile.

In light of these considerations, it is obvious that the nature of the correlation function (i.e., of the relationship between the correlation coefficient and the distance separating two locations) becomes a significant factor in the selection of sampling locations, especially in "higher level" geotechnical data acquisition programs. Therefore, part of the effort in this baseline data acquisition program should be aimed at defining the vertical and horizontal correlation structure of near-surface compressibility.

To achieve Sampling Purpose 2 (information about vertical correlation), Type A borings should comprise a fraction of the borings made for Purpose 1. Sampling Purpose 3 (information about horizontal correlation) requires a fairly dense array of borings along a line. A specific pattern is suggested in Figure 3.2. It consists of several arrays of equidistant borings, with different spacings for each array. The idea is that the different arrays will serve to identify the different components of inherent variation. (What is observed as a trend by a narrowly spaced array becomes part of the random variation observed by a widely spaced array.)

3.4.3 Sampling Purpose 4

To evaluate the variability of soil properties "at a point," it is useful to make a circular pattern of borings around the center of rotation of the drill rig. The variability of the test results for samples from these borings will be attributable to (a) local inherent variation, and (b) random measurement errors. It should be pointed out that this purpose is not as important as for Sampling Purposes 1 through 3; i.e., Purpose 3 also calls for a number of very close borings, so that the information gathered under Purpose 4 tends to be somewhat redundant.

3.5 OPTIMIZATION METHODOLOGY AND ILLUSTRATION

The optimization algorithm allocates borings to the different program purposes and attempts to optimize the spatial arrangement of borings allocated to each purpose. The specification requirements (number of data, type of borings, spatial arrangement) for the different tasks are stated below. From a statistical standpoint, the strength (quality, reliability) of predictions of probability distributions and parameters is directly dependent on the size of the data base from which they are derived. The margin of error in the estimate of a parameter decreases in inverse proportion to $\sqrt{n}$, where n is the number of independent observations. Judgement and experience suggest that at least 14 to 16 data points are needed to construct a data-based histogram, and that a minimum of 6-8 data points are needed to estimate variances or coefficients of variation with a reasonable degree of reliability.

There are four surficial soil types in Ralston Valley that cover approximately the same fraction of the total surface area. Assume that there will be n borings within each soil type, and therefore that the total number of borings will be $4n$. (In a more general case, the number of borings allocated might be roughly proportional to the fractions of the total surface area covered by each deposit.) For Sampling Purpose 1, Type B borings are acceptable. To avoid excessive time loss associated with drilling equipment relocation, Type B borings should be clustered in groups of three. But these clusters of borings should be widely spaced within the area covered by each surficial soil type to insure proper representation of other factors (e.g., distance from valley center, elevation, density, gradation, etc.).

Sampling Purpose 2 requires Type A borings spatially distributed in much the same way as the clusters of Type B borings for Sampling Purpose 1. In view of the time constraint on equipment movement, this strongly suggests that a pattern of four borings (three Type B and one Type A; i.e., Pattern I in

Figure 3.2) be repeated at widely scattered locations throughout Ralston Valley. To permit use of some of these borings to achieve Sampling Purpose 3 and to avoid excessive time loss to move the drilling rig, it is suggested that the four borings be located "on a line" at equal distances Δx_1 of about 500 feet. The time required to execute Pattern I is two days, and the cost is \$1,100 + \$1,200 = \$2,300 (see Section 3.3).

In addition to borings with spacing Δx_1, Sampling Purpose 3 also requires two relatively dense arrays of Type B borings, one with spacing Δx_2, the other with spacing Δx_3. Figure 3.2 shows how this proposed Pattern II makes use of borings already required for Sampling Purposes 1 and 2.

Sampling Purpose 4 requires a circular pattern of Type B borings placed at the site of an existing Type B boring; see Pattern III in Figure 3.2. Since the drilling equipment is stationary, five additional Type B borings can be made in one day at a cost of \$1,100 (according to specifications given in Section 3.3).

The major trade-off is between the intensity of effort under Sampling Purposes 1 and 2 (combined) versus the intensity of effort under Purpose 3. Recall that n is the number of boring locations in each soil type under Purposes 1 and 2. The number n is to be a multiple of four (one Type A and three Type B borings). We denote by k the number of equidistant intervals between borings for Sampling Purpose 3. Statistical considerations (mentioned previously) dictate that k and n must be approximately the same. A key question is whether the boring pattern required for the study of horizontal correlation (Pattern II) should be placed just once, or at two or three different sites (in areas with different surficial soil types)? The alternatives are investigated by using a simple optimization algorithm whose objective is to <u>maximize n</u>. The optimization is subject to the following constraints: (a) the total cost of boring and sampling must be less than \$60,000, (b) the time to perform the sampling program must be less than 55 days, and (c) the number n must be a multiple of 4. We denote by p the number of Pattern II or dense arrays of borings under Sampling Purpose 3. As shown on Figure 3.2, each such array requires $2(k - 2)$ additional Type B borings; therefore, the total number of borings for Sampling Purpose 3 is $2(k - 2)p$.

The equations for the total cost and time spent for Sampling Purposes 1, 2 and 3 are:

$$\text{Cost (\$)} \approx \frac{1{,}100}{3} [3n + 2(k - 2)p] + 1{,}200n$$

$$\text{Time (Days)} \approx \frac{1}{3} [3n + 2(k - 2)p] + n$$

To balance the amount of data acquired as part of each statistical data base, we impose the condition $k = n$. The cost and time data can now be computed for different values of $p(p = 1, 2, 3)$ and (for fixed p) for different values of $n(n = 4, 8, \ldots)$. The results of the computations are summarized in Table 3.1.

3.6 RECOMMENDED PLAN

The "suboptimal" solution under the third alternative ($p = 3$, i.e., three dense arrays) appears least desirable for two reasons. First, it gives a data base of only 12 points ($n = k = 12$). This is hardly sufficient for the purpose of constructing histograms and estimating scales of correlation. Second, the best solution under the third alternative ($p = 3$) "underuses" the available resources (time is underspent by 11 days, the budget by $10,400).

The first and second alternatives ($p = 1$ and 2) both provide acceptable solutions. The first alternative (with $n = 20$) may be expected to yield a smaller estimation error than the second alternative (with $n = 16$), but the latter will provide important backup information about horizontal correlation effects (in a different surficial deposit).

The best solution under the second alternative (i.e., $p = 2$ and $k = n = 16$) leaves sufficient time and money to spend some effort to meet Sampling Purpose 4. At the location of an existing boring, five additional Type B borings can be made in one day, at a cost of $1,100, to complete a six-boring circular pattern (see Section 3.3). Two such patterns can be included without violating the constraints. The total cost is now estimated at $59,900 and the total time requirement is about 53 days. The characteristics of the recommended sampling plan (based on the assumed constraints on the type and depth of borings and the sampling cost and time) are summarized in Table 3.2.

Note that the methodology permits evaluation of the time and dollar requirements of more intensive sampling programs which are infeasible under the assumed set of constraints.

Table 3.1 Alternative Sampling Plans for Purposes 1, 2 and 3

Number of Dense Boring Arrays	Borings In Each Surficial Soil Type	Number of Borings: For Sampling Purposes 1 and 2	Number of Borings: Additional For Sampling Purpose 3	Total	Time (Days)	Cost (Dollars)
p = 1	n = 12	48	20	68	~31	35,300
	n = 16	64	28	92	~42	47,800
	n = 20	80	36	116	52	59,800*
	n = 24	96	44	140	63	71,900
p = 2	n = 12	48	40	88	38	43,000
	n = 16	64	56	120	~51	57,700*
	n = 20	80	72	152	64	72,400
p = 3	n = 12	48	60	108	44	49,600*
	n = 16	64	84	148	60	67,600

* Denotes best solution for each value of p.

Table 3.2 Recommended Sampling Plan (p = 2; k = n = 16)

Sampling Purpose	Boring Pattern (see Fig. 3.2)	Number of Patterns	Incremental Number of Borings
1 and 2	I	16	64
3	II	2	56
4	III	2	10

Note: Total number of borings = 130.
Estimated total cost = $59,900.
Estimated total time = 53 days.

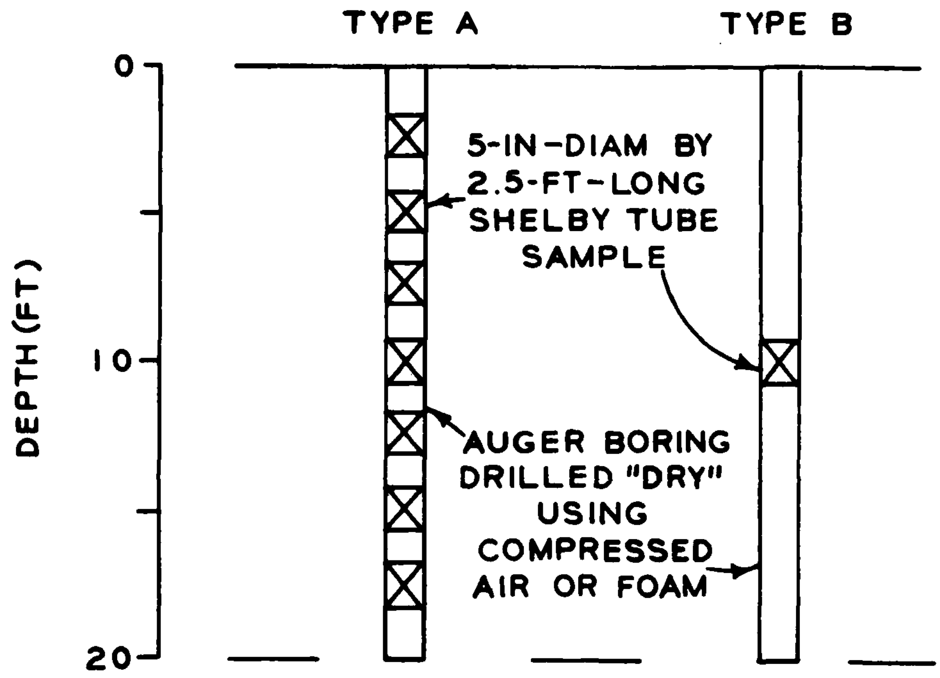

Figure 3.1 Boring types and lengths considered in sampling plan design.

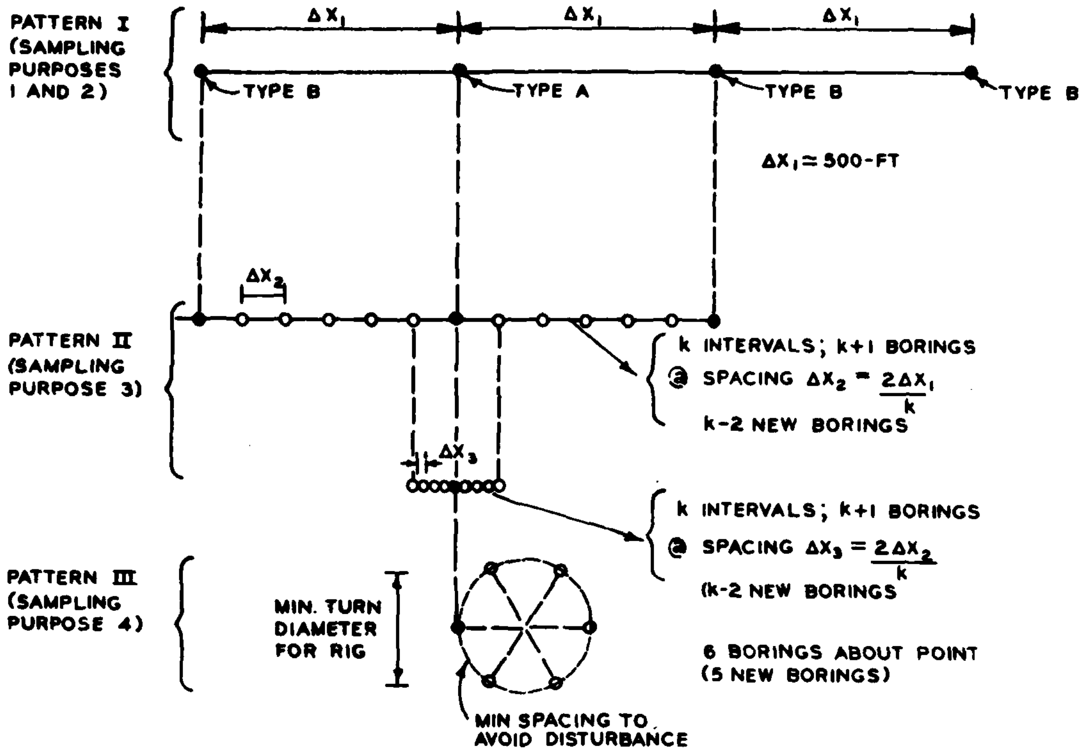

Figure 3.2 Boring patterns suggested for specific sampling purposes.

CHAPTER 4

EPILOGUE

The recommended sampling plan for Ralston Valley was briefed to DNA and Air Force representatives and approved for implementation as outlined; there were also two significant additions. The first involved extending the characterization from a depth of 20 feet to a depth of 160 feet; this was accomplished by converting eight of the Type A borings (see Figure 3.1) into one Type C and seven Type D borings, as depicted in Figure 4.1. Thus boring Pattern I now has three variations, i.e., Patterns Ia, Ib, and Ic as shown in Figure 4.2. Also note that 3-inch-diameter Pitcher tube samples are indicated in lieu of the previously specified 5-inch-diameter Shelby tube samples. This change was made for all borings so that some shear tests can be performed along with the compressibility tests. While the larger samples are generally preferred for obtaining uniaxial strain compressibility test specimens, undisturbed triaxial shear test specimens can be obtained from the smaller diameter samples without circumferential trimming, a procedure which has proven to be virtually impossible with dry gravelly sands.

The second addition to the program involved having Fugro perform seismic refraction surveys at each boring location in order to obtain P-wave velocity measurements that can be directly compared with results from the uniaxial strain tests and be subjected to similar probabilistic analyses. Refraction spreads of 120 feet and 60 feet were designed with 5-foot geophone spacings provide detailed information on velocity profiles in the upper 20 to 40 feet, 600-foot spreads with 25-foot geophone spacings were specified to provide data to depths of 150 to 200 feet at the eight Type C and D boring locations.

The plan was completed for field execution by locating 16 sites on a Fugro-furnished 1:62,500-scale map such that:

(a) there would be four sites in areas designated by each of the four primary surficial geologic units (i.e., A5y, A5i, Au and A4/Au);

(b) the four locations selected for each surficial unit would include a wide range of distance from the mountains, distance from the playa lake bed, distance from the valley centerline, and surface elevation; and

(c) all sites would be located adjacent to existing roads in order to minimize potential problems with both access of equipment and archaeologic disturbance.

The site numbers and their locations are shown in Figure 4.3; estimated distances and surface elevations are given in Table 4.1 along with the boring patterns to be staked at each site.

Table 4.1 Selection criteria distances, surface elevations, and boring patterns for Ralston Valley sampling locations

Site Number	Estimated Distances (mi) From Mountains	From Playa	From Valley ℄	Approx Elevation (ft)	Boring Patterns
RA5Y	2.33	16.42	3.34	5580	Ib, II, III
RB5Y	3.24	14.09	0.78	5540	Ia
RC5Y	1.93	10.23	4.54	5480	Ic
RD5Y	0.91	0.76	3.77	5240	Ia
RA5I	1.42	20.24	0.77	5820	Ic
RB5I	1.11	15.66	5.47	5680	Ia
RC5I	0.76	11.27	6.17	5680	Ic
RD5I	0.58	4.97	5.37	5480	Ia
RAU	1.62	18.14	2.38	5600	Ic
RBU	4.73	9.03	1.75	5370	Ic, II, III
RCU	2.33	0.76	2.45	5200	Ia
RDU	2.23	3.39	6.63	5255	Ia
RA4U	4.26	13.43	0.76	5470	Ia
RB4U	5.67	8.53	1.06	5330	Ic
RC4U	6.33	3.24	0.35	5250	Ic
RD4U	3.04	3.70	4.46	5215	Ia

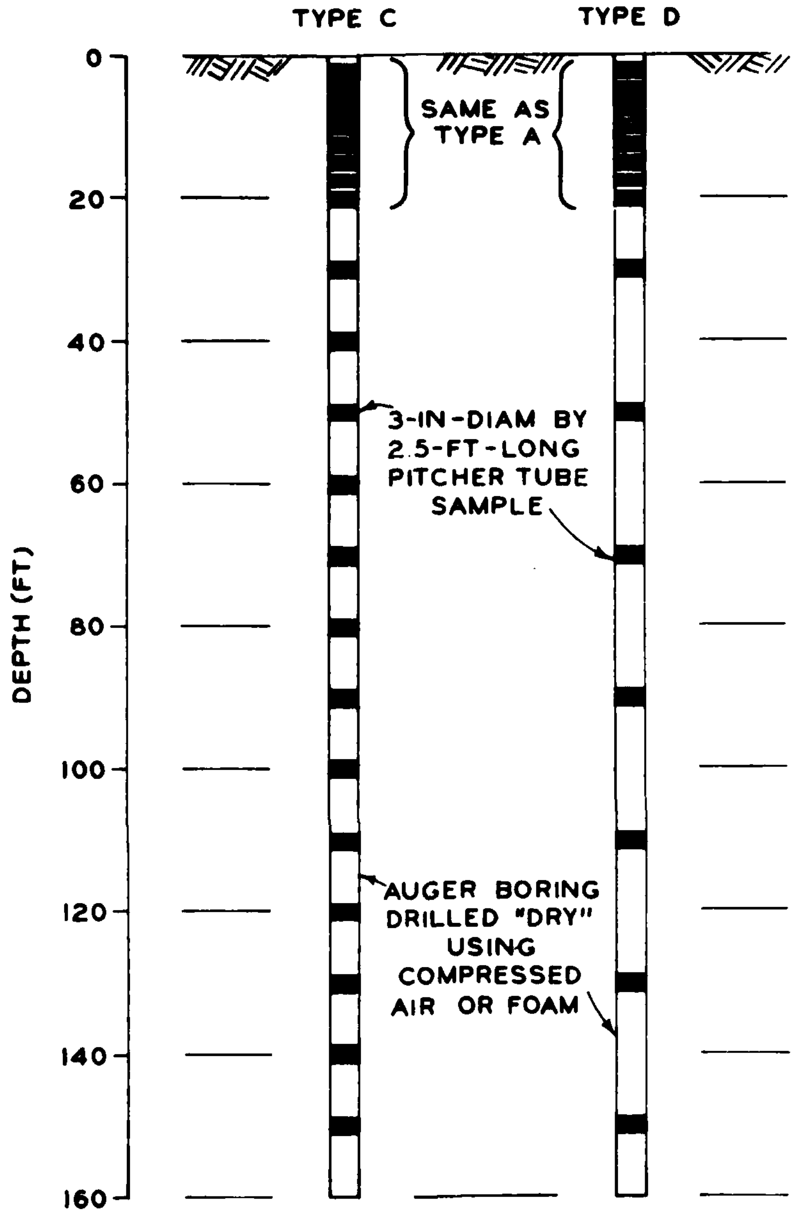

Figure 4.1 Boring types and lengths added to extend characterization depth.

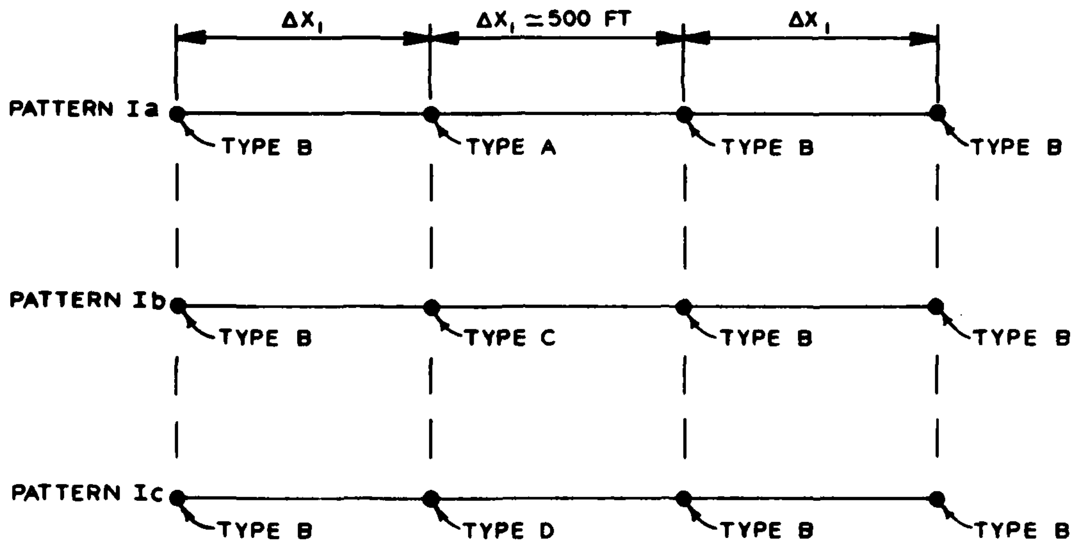

Figure 4.2 Boring Pattern I variations added to extend characterization depth.

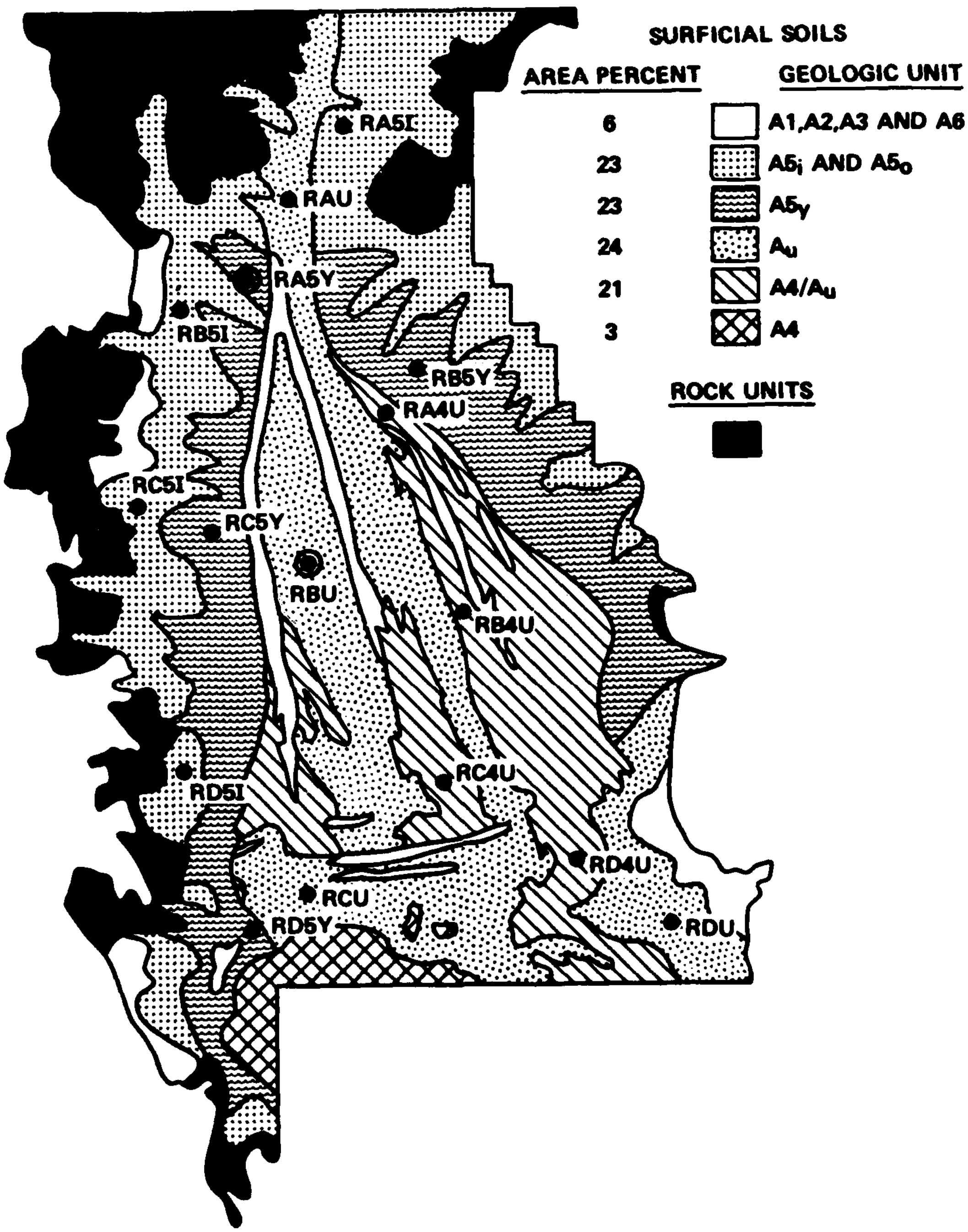

Figure 4.3 Site numbers and locations for Ralston Valley probabilistic sampling plan.

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