H-Area/ITP Geostatistical Assessment of In-Situ and Engineering Properties

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DOE Contract No. DE-AC09-96SR18500

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**H-Area/ITP Geostatistical Assessment
of
In-situ and Engineering Properties**

**Final Technical Report
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**ERDA Project Number: 93044
In Response to:
SRS Request for Proposal Number 93044EQ
January 4, 1994
(Revised Statement of Scope Number 93044, Revision 0, December 1,
1993)**

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September 5, 1995

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EXECUTIVE SUMMARY

Preliminary field investigations performed for the seismic qualification of the ITP facility identified two issues concerning the foundation soils: (1) potentially liquefiable soils in the upper strata, and (2) a deeper zone of apparently under-consolidated calcareous sediments in the Santee Formation. To estimate the potential amount of surface settlement resulting from a seismic event, WSRC (1995) developed a program plan which detailed further field measurements and subsequent analysis and numerical modeling. As part of developing soil-properties input to this modeling, senior peer reviewers raised questions about how to properly assess the large amount of observed soil variability and how to incorporate the scale of that variability in a manner consistent with the discretization size of the mesh.

Further, the WSRC program plan outlined a probabilistic liquefaction hazard evaluation requiring a stochastic approach to modeling and reliability. To these ends, geostatistical analyses of CPT and SPT measurements from the ITP site were conducted. The results are:

Borehole Data Structure: The borehole data structure displayed a number of distinct characteristics. First, the three-dimensional data resolution was highly imbalanced, with very tight resolution in the vertical direction and orders of magnitude wider resolutions in the lateral direction. This is typical of borehole data because sampling intervals in the vertical direction in a given borehole are on the order of inches to a few feet; whereas, horizontal spacing between boreholes usually varies on the order of tens to hundreds of feet. This imbalance makes three-dimensional estimation somewhat problematic, especially in the horizontal plane. Second, the geological formations clearly exhibited a multi-layer stratigraphy with differing features. Based on these distinct features, each borehole data were divided into a number of substrata by the geological and geotechnical staff at WSRC. Third, the preliminary stratigraphic model of the site showed evidences of faulting and other

discontinuities in the layered structure.

Complicated Intra-layer Variations: Despite the initial grouping of the borehole data into a number of substrata, in-situ measurements within each layer displayed complicated vertical and lateral variations. These variations, however, were only partially explainable based on deterministic geological and geotechnical models. Therefore, the use of statistical methods became inevitable.

Suitable Statistical Tool: Among statistical methods, geostatistical algorithms appeared to be the most suitable due to a number of reasons. First, geostatistics recognizes the multi-layer, three-dimensional structure of the borehole data. Second, unlike classical statistical procedures, geostatistics incorporates the potential spatial (auto-correlational) structure of the collected data. Third, vertically clustered borehole measurements can be processed by geostatistical methods. Finally, geostatistics offers both estimation and simulation procedures that can be used in a variety of applications.

CPT Variography and Estimation Results: The variography along the vertical direction (i.e., down the borehole) revealed well defined structures with ranges varying between 2 to 12 ft, suggesting geological bedding on a scale of this size. The results of the omni-directional lateral variograms revealed more complicated structures than the vertical variograms. The lateral variogram range for different layers varied from 40 to 130 ft, except for the Santee Formation which exhibited a lateral pure nugget effect. This implied that the horizontal dimension of the soft zones in the Santee Formation is less than the lateral resolution of the available CPT data.

Using the appropriate vertical and lateral variograms, kriging was used to interpolate CPT tip and sleeve resistances to a FLAC mesh for liquefaction and settlement analyses. The interpolated values were done layer-by-layer to preserve the multi-layered structure at ITP.

Soft Zone Categorical Variography in the Santee Formation: Attempts to define the lateral dimensions of the soft zones in the Santee Formation were unsuccessful using the CPT data solely. Thus, the SPT borings were also analyzed because of their denser horizontal spacing in the following manner. Measured CPT tip resistances and SPT $(N_1)_{60}$ values in the Santee Formation were categorized into three groups as: Soft, Intermediate, and Stiff soils. Soft soils were defined as sediments having $(N_1)_{60}$ values less than 5 or CPT tip stresses less than 15 tsf. Intermediate soils have $(N_1)_{60}$ values between 5 and 10 or CPT tip stresses between 15 and 40 tsf. Stiff soils have $(N_1)_{60}$ values greater than 10 to CPT tip stresses greater than 40 tsf. Results indicated that: (a) The soft soils have an average thickness of less than 4 ft. (b) The average thickness of the combined soft/intermediate soils appeared to be less than 8 ft. The combined soft/intermediate soils had a vertical variogram that was not as well-defined as the one for the soft soils). (c) Neither the soft soil, nor the combined soft/intermediate soils showed any discernable lateral correlations. (d) In the absence of lateral discernable correlation, the lateral extent of the soft soils and the combined soft/intermediate soils was approximated to be less than the average borehole spacing which is 35 ft.

Shear Wave Variography and Simulation Results: The analysis of shear wave data was initiated by dividing the soil volume in the investigated area into seven different layers: Fill, TR1, TR2, TR3/TR4, DB1/DB4, DB5, and ST. This approach, however, yielded undue discontinuities along the dividing surfaces of the various layers which produced unwanted and artificially high impedance contrasts for dynamic modeling. Therefore, in subsequent simulations the complete formation was considered as a single unit. These simulated results indicated that each simulated profile preserved the spatial variabilities exhibited by the original values.

SPT Simulation versus Estimation Results: For a liquefaction hazard, $(N_1)_{60}$ values were geostatistically simulated and estimated. The comparison of results indicated that: (a) estimation (kriging) results were overly smooth in sparsely sampled

locations. (b) Conditional simulation results, on the other hand, preserved the variability of $(N_1)_{60}$ values in both dense and sparsely sampled locations. (c) Simulations were significantly more time consuming than estimation. However, in cases where geostatistical results are intended to be used as input into other numerical models and preservation of the stochastic variability of these inputs are critical to the study objectives, then simulation rather than estimation should be used.

1.0 INTRODUCTION

The following technical report describes the results of a geostatistical investigation conducted in response to tasks and requirements set out in the SRS Request for Proposal Number 93044EQ, dated January 4, 1994. The project tasks were defined in the Statement of Scope (SOS) Number 93044, Revision 0, dated December 1, 1993, developed by the Savannah River Site Geotechnical Services Department.

Foundation investigations performed as part of the ITP Geotechnical Investigation have identified two issues of concern: (1) potential liquefaction susceptibility of some strata and (2) a zone of apparently under-consolidated soil that appears to be associated with dissolution of calcareous sediments. Liquefaction and/or dynamic settlement of these potentially unstable soils could cause differential settlement during seismic event. If the differential settlement is larger than that which can be tolerated by the ITP tanks, loss of tank integrity could occur.

The assessment of the foundation for the ITP tanks involves a large number of parameters that exhibit complex spatial structures. The primary objectives of this investigation included: (1) identification and/or development of appropriate geostatistical tools for analysis of spatial geotechnical data; (2) geostatistical analyses of in-situ and engineering properties of interest; and (3) estimation and/or simulation of properties of interest as the required input into the engineering evaluations and models used to calculate the static and dynamic stability of the embankment and foundation soils.

The geostatistical investigation was conducted along with a number of other planned activities, including preliminary evaluation of OCR from SCPT data by Prof. P. W. Mayne at Georgia Tech. A summary report of this latter activity is included in Appendix III.

1.1 OBJECTIVES

The geostatistical and statistical analyses described were conducted in order to provide input into the engineering evaluations and models used to calculate the static and dynamic stability of the embankment and foundation soils. Four types of engineering evaluations were planned: (1) dynamic soil response, (2) static and dynamic slope stability, (3) liquefaction susceptibility, and (4) static and dynamic settlement. In addition to these activities, geostatistical techniques were applied to describe the spatial distribution of the geological strata in the ITP/H-Tank Farm Area as a part of "Geologic Setting" Task of in Phase II of the H-Area/ITP Geotechnical Service Program Plan (SGS-ENG-93001).

The specific purposes of the geostatistical analyses described in this report were:

- (1) Providing the best possible estimates of the mean and variance of the in-situ geotechnical measurements for a given stratum and/or location by accounting for the spatial correlations of these data;
- (2) Using the above best possible estimates of the in-situ measurements to predict engineering properties for a given layer and/or location by using existing geotechnical correlations;
- (3) Providing a means for the evaluation of the performance of these correlations by comparing the predicted values with field measured results;
- (4) Providing the engineering modelers with the spatial distribution and probable range of predicted engineering properties, through appropriated kriging or simulation procedures by taking into account the variability within a given

stratum, the uncertainty in interpolating the in-situ measurements to an unmeasured location, and the uncertainty associated with the correlations used to predict the engineering properties from the in-situ measurements.

1.2 AVAILABLE DATA

The data used in this investigation include various types of borehole measurements from within the ITP facility, hereinafter referred to as "the site." The map of the site and a number of borehole locations are shown in Figure 1.2.1.

The underlying geological formation at the site has been divided into a number of substrata as listed in Table 1.2.1. The WSRC geological and geotechnical staff used CPT data and soil samples from nearby SPT borings to corroborate the layer boundaries at twenty CPT locations, as presented in Appendix IV. The selected layer contacts show a marked change in the in-situ properties and the layers have sufficient thickness so as to be traceable across a significant portion of the site. These layer contacts were used to define sub-layer surfaces for subsequent geostatistical analyses.

The available in-situ measurements which were provided by WSRC are listed in Appendix V. These in-situ measurements can be grouped as follows:

CPT Data: Cone Penetrometer soundings (CPT) borehole data include: borehole easting, borehole northing, borehole surface elevation, measurement depth, tip resistance, q_c ; sleeve friction, f_s ; friction ratio, FR; pore pressure measured behind the tip, u ; and the Soil Classification Number, SCN.

SPT Data: Standard penetration tests (SPT) data include: borehole easting, borehole northing, borehole surface elevation, measurement depth, uncorrected blow count, N ; and corrected blow count, $(N_1)_{60}$. In addition, Dr. S. F. Bartlett provided

predicted $(N_1)_{60}$ values based on site-specific correlations of CPT data with SPT data. The CPT data were converted to $(N_1)_{60}$ using regression analysis between available SPT and CPT data. The regression analysis and the correction of SPT N values to $(N_1)_{60}$ values were conducted by WSRC personnel.

Shear Wave Data: This data set includes a number of downhole and cross-hole shear wave velocity measurements (i.e., V_s) at the site.

2.0 GEOSTATISTICAL METHODOLOGY

A general introduction to geostatistics is presented herein as background to various analyses conducted in this project. Geostatistics (Matheron, 1971; Journel and Huijbregts, 1978, Isaaks and Srivastava, 1989) are a collection of techniques for the analysis of spatially correlated data. Geostatistical techniques incorporate the spatial characteristics of actual data into statistical estimation processes. Geostatistics permit the performance of critical tasks, such as: optimization of spatial mapping for physical processes, estimating average block values, and the design of sampling and monitoring schemes. In statistical terms, geostatistics provides tools for extraction of maximum amount of information from the available data.

In-situ measurements collected at different locations within the same site usually display a wide range of variability. As a result, the magnitude of the variable under investigation at an unmeasured location cannot be predicted with certainty, even if this variable was measured at other nearby boreholes. Such erratic variations have led many to use classical (i.e., non-spatial) statistical estimation methods. These methods usually assume that the collected data to be unbiased, unclustered, and independent (i.e., devoid of any correlational structures). In practice, however, borehole data are collected in a biased fashion, are clustered in the vertical direction, and are expected to display a degree of spatial structure. Geostatistics recognizes these properties and, according to well-defined criteria, provides the statistical tools for:

- (1) Calculating the most accurate estimations based on sample results and other relevant information;
- (2) Quantifying the accuracy of these estimations;
- (3) Generating equally-likely realizations of a random field conditional to the

available in-situ measurements; and

- (4) Selecting the variables and locations to be sampled, if necessary.

The United States Environmental Protection Agency (U.S. EPA) has taken the lead in promotion of geostatistics by producing the first public-domain software package, known as GEO-EAS (Geostatistical Environment Assessment Software) developed by Englund and Sparks (EPA/600/4-88/033a, 1988). This package was followed by another EPA package, known as GEOPACK, developed by Yates and Yates (EPA/600/8-90/004, 1990). The successful results of application of GEO-EAS prompted the U.S. EPA to recommend its use in spatial environmental data analysis, as stated in "Guidance for Data Usability in Risk Assessment" (EPA/540/G-90/008, 1990) and "Basics of Pump-and-Treat Ground-Water Remediation Technology" (EPA/600/8-90/003, 1990).

The main features of linear geostatistics to be applied are:

- (1) Geostatistics provides models of the spatial continuity of data in a statistical framework. For example, within a layer, data points which are closer in a given direction are assigned a specific correlation value. These correlation values are estimated based on available data in that layer.
- (2) Geostatistical point or block estimates are calculated as weighted sums of the adjacent sampled values. These weights depend on the exhibited correlation structure. For example, if data appear to be highly continuous in space, the points which are closer to the estimated points will receive higher weights than those further away. The criterion for selection of these weights is the minimization of estimation variance. In this framework, geostatistical estimates may be regarded as the most accurate estimates among linear estimators (i.e., Best Linear Unbiased Estimator), implying that the geostatistical estimation

processes are based on well-defined criteria, and thus are superior to subjective estimation techniques.

- (3) Geostatistical techniques can process sample results averaged over different volumes and sizes. In other words, depending on whether the estimation is a point or block value, geostatistics will yield different results, consistent with the geometry of the estimation domain.
- (4) Geostatistics provides tools for simulation of equally-likely realizations of the investigated random fields. These simulations can respect the available measured values. Such simulated results are specially useful in cases where the preservation of the spatial variability of the investigated process is critical to the study objectives.

For a more detailed review of geostatistics, readers are referred to ASCE (1990a and 1990b).

2.1 GEOSTATISTICAL STRUCTURAL ANALYSIS

The first task in any geostatistical investigation is to identify the spatial structure of the investigated variable in a given area. This task is usually done by developing the sample *variogram* of the collected data. EPA/600/4-88/033a defines the variogram as the plot of the variance (one-half the mean squared difference) of paired sample results as a function of the distance between samples

$$\gamma_{ij} = \frac{1}{2}E[Z_i - Z_j]^2 \quad (1)$$

where

γ_{ij} = (semi-)variogram between Z_i and Z_j ;

Z_i = a random variable representing investigated variable at location x_i ;
and
 E = expected value operator.

Variograms quantify the commonly observed relationship among geo-data. Such relationships usually indicate that close-together samples will tend to have more similar values than those far apart. In this respect, the variogram can be regarded as a measure of the degree of (dis)association, as displayed by available data.

Three main parameters of a typical variogram are: (1) range, (2) sill, and (3) nugget effect. Range is the distance at which the variogram reaches its maximum value. Paired samples whose separation distance is greater than the range are uncorrelated. Therefore, the range is regarded as a measure of spatial continuity of the investigated variable. The sill is the upper limit of any variogram where the variability tends reaches a limiting value at large separation distances. The sill is a measure of the population variability of the investigated variable; the higher the sill, the greater the variability in the population. A nugget effect is exhibited by the apparent jump of the variogram at the origin, which is usually attributed to small-scale variability of the investigated data and/or to measurement errors.

Because of the three-dimensional nature of the available data at ITP a number of variograms are computed and modeled as follows:

- (1) Variable-specific Vertical Variograms: These are unidirectional vertical variograms which are computed for each substratum separately.
- (2) Variable-specific Lateral Variograms: These are stratum-specific variograms where lateral separation distances are measured parallel to the top and bottom surfaces of the substratum. Lateral stratum-specific variograms are specially useful when processing data from formations with non-horizontal stratigraphies

or nearly horizontal stratigraphies that have been affected by faulting.

- (3) **Marker Surface Variograms:** These horizontal variograms are needed for estimation of the elevation of the dividing surfaces between various substrata. The data for building such variograms are the elevation of each substratum markers. These elevations were determined by the geological and geotechnical staff at WSRC, as shown in Appendix IV.

2.1.1 VARIOGRAPHY

The type and parameters of the variogram model must be determined based on the available information. This process, known as variography, is conducted through the use of an appropriate geostatistical software that permits the visual fitting of acceptable variogram model(s) to the computed sample variograms. Variography is initiated by grouping the available pair-values according to their vertical or lateral separation distances into a number of lags or distance classes. Ideally, twenty or more pairs should be present in each lag. The arithmetic average of one-half of differences squared, $1/2(z_i - z_j)^2$, of all pairs in a given lag is defined as the sample variogram of that distance class. Upon computation of sample variograms, four iterative steps are taken: (1) selecting an acceptable mathematical model to fit the sample variograms, (2) visually determining a reasonable sill value for that model, (3) determining the nugget value, and (4) visually selecting a reasonable range. Using the chosen parameter values, the variogram model is superimposed on the sample variogram values. At this stage, the analyst modifies the parameter values until a satisfactory visual fit is achieved.

Because the near-origin characteristics of the fitted model have the most important influence on the estimated values, the above process is primarily controlled by near-distance sample variograms. Consequently in visual model fitting, more

emphasis is given in closely matching the sample variograms near the origin and less emphasis is given to the far-distance sample variograms.

2.2 GEOSTATISTICAL ESTIMATION

Upon determination of the variogram model, the linear geostatistical estimation process known as ordinary *kriging* can be performed as

$$Z_o^* = \sum_{i=1}^n \lambda_i z_i \quad (2)$$

where,

- Z_o^* = Estimated point or block value centered at x_o ,
- z_i = Measured value at x_i ,
- λ_i = Estimation weight of z_i .

The computation of the above estimation weights are conducted on the basis of two criteria, which are:

- (1) Non-Bias Condition:

$$E[Z_o^* - Z_o] = 0 \quad (3)$$

This condition ensures that there will be an absence of systematic error. If it can be assumed that the measured values have the same mean, whose magnitude is unknown, then this condition is reduced to:

$$\sum_{i=1}^n \lambda_i = 1 \quad (4)$$

- (2) **Minimum Variance of Estimation:** This condition ensures that the estimation variance of the interpolated value, whether point or block value, to be minimum. In statistical terms, the resulting estimate is viewed as the most accurate linear estimate. The estimation variance is only a function of the variogram and the estimation weights, which can be defined as

$$Var(Z_o^*) = -\sum_{i=0}^n \sum_{j=0}^n \lambda_i \lambda_j \gamma_{ij} \quad (5)$$

where,

$$\begin{aligned} \gamma_{ij} &= \text{Variogram function between } Z_i \text{ and } Z_j; \text{ and} \\ \lambda_o &= -1. \end{aligned}$$

The minimization of the estimation variance subject to the non-bias condition is accomplished through the Lagrange multiplier approach, yielding the following kriging system:

$$\begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} & 1 \\ \vdots & \vdots & & \vdots & \vdots \\ \vdots & \vdots & & \vdots & \vdots \\ \gamma_{n1} & \gamma_{n2} & \cdots & \gamma_{nn} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \vdots \\ \vdots \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} \gamma_{o1} \\ \vdots \\ \vdots \\ \gamma_{on} \\ 1 \end{bmatrix} \quad (6)$$

where μ = Lagrange Multiplier. In case of block kriging, γ_{oi} in the right-hand-side vector must be replaced by γ_{Vi} , which is the average variogram between the targeted block V and the measurement value located at x_i .

In this project, ordinary kriging was mainly used to perform point kriging for generating nodal estimates which were then contoured to form multi-layer or three-dimensional

maps of various soil properties.

2.3 GEOSTATISTICAL SIMULATIONS

Because kriging yields weighted-average estimates, it fails to preserve the variability of the original data; instead, kriging produces interpolated results that are "smoothed." However, in stochastic modeling, the preservation of the spatial variability is specially important if the processed data are aimed to be used as inputs into other statistical or numerical models. For example, in this project, the use of kriged in-situ properties in a probabilistic liquefaction assessment (Liao, 1986; WSRC, 1995) can yield erroneous results. This problem is mainly due to the fact that the interpolated values based on kriging display a lower variation than the actual measured values. Such under-representations of the variability tend to under-estimate the number of low SPT $(N_1)_{60}$ values which control the liquefaction response and ultimately underestimate the liquefaction hazard.

To correct the above deficiency, geostatistical *simulation* can be used (Journel and Huijbregts, 1978). The purpose of simulation is to generate sets of equally-likely outcomes which are consistent with the observed in-situ measurements. In geostatistical simulation, this often means that the simulated values have the same mean and variogram as the original data, and in the case of conditional geostatistical simulation, the simulated values must equal the observed data at the measurement points (Journel and Huijbregts, 1978). While kriging provides an estimate of the average value of $Z(x)$, geostatistical simulation yields one of the several possible outcomes of $Z(x)$ that respects the above criteria.

Typically simulation is used to generate several different spatial sets of the property of interest in order to run a deterministic model, repeatedly in a Monte Carlo type approach. The resulting set of model outputs are treated as equally-likely

outcomes and can then be used to define the probability distribution of the modelled response.

For the ITP probabilistic liquefaction hazard assessment, conditional simulation techniques were used (WSRC, 1995). There are a number of procedures for performing this type of simulation. An effective numerical procedure is the Sequential Gaussian Simulation. In this process, upon the gaussian transformation of the available in-situ measurements, simulation is conducted, such that each simulated value is conditioned on the original data and all previously simulated values (Deutsch and Journel, 1992).

2.4 GEOSTATISTICAL SOFTWARE

In this investigation three major software packages were used. These were: (1) U.S. EPA's GEO-EAS, (2) Stanford's Geostatistical Library (GSLIB), and (3) RC²'s ResMod. The following paragraphs provide a summary description of these software packages.

GEO-EAS: The most commonly used public domain geostatistical software is U.S. EPA's GEO-EAS (Geostatistical Environmental Assessment Software) by Englund and Sparks (1988). GEO-EAS is basically a collection of interactive tools for two dimensional geostatistical analysis of spatially distributed data. This software provides the following programs:

- (a) DATAPREP for data file management;
- (b) TRANS for mathematical transformations of data;
- (c) STAT1 for univariate statistical computations;
- (d) PREVAR and VARIO for two-dimensional variogram analyses;
- (e) XVALID for cross validation of estimated results;

- (f) KRIGE for two dimensional point or block kriging;
- (g) CONREC for two dimensional contour mapping;
- (h) POSTPLOT for measurement locations mapping;
- (i) XYGRPAH for simple linear regression computations.

GEO-EAS offers point and block kriging techniques. Kriging can perform spatial interpolation based on correlated data, spatially biased samples, anisotropic variables, and/or clustered data set. It also generates the estimated variance that can be used as a measure for the accuracy of each interpolated value.

GSLIB: GSLIB (Deutsch and Journel, 1992) is a geostatistical software library developed at Stanford University. GSLIB programs are developmental tools and sketches for custom programs, advance applications and research. These programs are a set of FORTRAN source code for various geostatistical computations. These source codes can be modified for special applications. Various computations, such as variography, kriging, and simulations, can be performed by the different programs in GSLIB. GSLIB is coded to the ANSI standard to achieve machine independence, thus, its use is not limited to a specific PC, workstation or mainframe computer. In this project, programs for: (a) three-dimensional variogram analysis, (b) three-dimensional regular grid kriging, and (c) three-dimensional irregular grid kriging were used.

ResMod: This Unix-based software is developed by *(RC)² Reservoir Characterization, Research & Consulting, Inc.* The program is divided into three sub-programs: ResPrep, ResGram, and ResMod. ResPrep is a gateway for the analysis of borehole data. The borehole data include borehole ID, Easting, Northing, Elevation, Deviation of elevation, Depth Markers, Time Markers, Depth logs, and Time Logs. This program formats the data into a binary standard data format called HDF as defined by the NCSA (National Center for Supercomputing Applications). HDF allows the binary data to be completely portable across the platforms. Besides reformatting

the data, ResPrep serves another important function of creating fast load log files in either depth and/or time. ResPrep generates following files:

- (1) CATALOG_WELLS: a text file that controls the list of well files that are loaded.
- (2) Well files which contains all of the depth/time markers, logs and geometric information for a given well which are created based on the input ASCII files.
- (3) Fast load well log files which contain well log information.

Upon completion of ResPrep tasks, ResGram is used to compute and construct models of spatial variabilities, including variograms. In a multilayer, three-dimensional environment, different types of variograms must be defined, such as (a) vertical variograms, (b) lateral variograms, and (c) marker surface variograms.

After variogram modeling, ResMod can be used to generate three-dimensional estimated or simulated maps for visual inspections as well as assessing local and global uncertainties. The modeling algorithms are mainly geostatistical techniques based on kriging and simulation procedures. The geostatistical algorithms are based on GSLIB. Some of the GSLIB codes have been modified to make them more flexible. In addition, there are several options which are not currently available in GSLIB or any other source. In this project, ResMod was used for three dimensional, ordinary kriging and the sequential gaussian simulation.

3.0 GEOSTATISTICAL ANALYSIS OF CPT DATA

The CPT data from twenty soundings were subjected to geostatistical analysis. These CPT soundings are listed in Table 3.0.1 and partially identified in Figure 1.2.1.

The review of the above CPT data revealed a number of reported values which were viewed as inconsistent with the geology of the site. To ensure the quality of the geostatistical works these erroneous values were removed. The reported corrections are grouped as follows:

Negative Friction Ratios: A few points in the CPT soundings reported negative friction ratios. Some negative values were reported where the sleeve had measured slightly negative side friction. During preliminary analyses, each borehole data was checked separately and the spurious friction ratio data were removed for this case. The removed negative friction ratio data are listed in Table 3.0.2. Also, at few locations, negative friction ratios were reported due to slightly negative tip resistances. Because these increments may represent soft zones, their corresponding tip resistances were preserved in the data set, as listed in Table 3.0.3; however, the corresponding friction ratios were removed.

Spurious Fill Data: In a letter dated March 30, 1994, Dr. S. F. Bartlett of WSRC reported that his review of kriged results revealed some spurious data in the top of the fill near the ground surface. According to him: " [t]hese data are near ground surface where the cone penetrometer was at the beginning of its push, or where the pilot hole was dug to seat the penetrometer." All measured values at these suspect depths were removed as listed in Table 3.0.4.

Large Friction Ratios: At some intervals the measured friction ratios are all positive, but are extremely high. This is due to a very low tip stress which

approaches zero. The use of such anomalous friction ratios could adversely impact the kriging results. Therefore they were removed, as listed in Table 3.0.5. However, as before, the low tip resistances were preserved in the data set because they may represent soft zones.

Estimation of tip resistance values and friction ratio values along vertical cross-sections A-A' and B-B', as shown in Figure 1.2.1, were conducted before and after the removal of the above suspect data. The kriging results after the removal of the erroneous friction ratio data showed satisfactory results.

3.1 VARIOGRAM ANALYSIS OF CPT DATA

Different variogram analyses of CPT data were conducted. These computations were aimed at deciphering the underlying structures of various substrata. For this purpose tip resistance data were used in both their original and transformed conditions. The following subsections provide a summary of these analyses.

3.1.1 MULTILAYER VARIOGRAM

The CPT data from the twenty boreholes were subjected to multilayer variogram analyses. For this purpose, the data was divided into the pre-defined sublayers as listed in Table 1.2.1.

The variography along the vertical direction revealed well defined structures with ranges varying between 2 to 12 ft, as shown in Figure 3.1.1 through Figure 3.1.10 and listed in Table 3.1.1. The sills of these vertical variograms are from 410 to 9000 tsf² as shown in Table 3.1.1.

The lateral variography was done along the direction parallel to the dividing surfaces (i.e. marker surfaces) of each substratum. Modified GSLIB programs and ResGram were used for such (pseudo)-horizontal variographic computations. The results of the omni-directional lateral variogram revealed structure with much wider ranges than the vertical variograms. These lateral ranges varied from 40 to 130 ft, as shown in Figure 3.1.1 through Figure 3.1.10. For modeling purposes, the type of the lateral variograms were assumed to be determined by the type of their corresponding vertical models. These latter models are based on high-resolution vertical data, and thus, are reliable representation of the intra-stratum variations at small scales. The horizontal ranges, however, were fitted directly based on the lateral sample variograms. The resulting fitted variogram were three-dimensional anisotropic models. Such models are also consistent with the depositional nature of the investigated multi-layer formation. As the previous figures indicate such a modeling approach yields satisfactory results.

As shown in the above figures and Table 3.1.1, the Santee Formation exhibited a lateral pure nugget effect and a vertical variogram with a range of 6 ft along the vertical direction.

3.1.2 SOFT ZONES CATEGORICAL VARIOGRAM ANALYSIS (CPT DATA)

To further explore the structure of soft zones in the Santee Formation an indicator approach was used. For this purpose, measured tip resistances in the Santee Formation were categorized into three groups as:

- (1) Soft soil (tip resistances less than or equal to 15 tsf),
- (2) Intermediate soil (tip resistances between 15 and 40 tsf), and
- (3) Stiff soil (tip resistances greater than 40 tsf).

These categorical data are equivalent to two sets of indicator variables. Soft soil

categorical data is equivalent to Indicator #1 (soft versus non-soft soil), and Stiff soil categorical data equals Indicator #2 (non-stiff versus stiff soil).

All the above categorical values were then subjected to variogram analyses. Initially omni-directional lateral and vertical variograms were computed and modeled, as shown in Figures 3.1.11 through 3.1.13. These variograms consistently displayed lateral spatial structures of pure nugget effect. This implies poor spatial structure or correlation in the lateral direction within the Santee Formation.

A series of directional lateral variography for the above categorical variables were conducted along the southwest-northeast "trend" in the Santee Formation. Three specific direction-angles of 30°, 45°, and 60° were tested, as shown in Figures 3.1.14 through 3.1.22. These angles roughly parallel the western edge of the carbonate body and the strike of an interpreted fault (WSRC, 1995). This directional variography was done to see if the soft zones have a preferred orientation that parallels these subsurface structures. If so, this might imply a causal link between faulting and the apparent dissolution that has produced the soft zones along the fringe of the carbonate body. None of these directions indicated the presence of any discernable lateral correlations. Along these directions, the soft soils have a lateral extent of less than 35 ft and the lateral extent of the combined soft/intermediate soils (Indicator #2) is less than 50 ft.

The results of the vertical and lateral variography indicate that: (a) the soft soils had an average thickness of less than 4 ft and (b) the average thickness of the combined soft/intermediate soils appeared to be less than 8 ft. The combined soft/intermediate soils (Indicator #2) had a vertical variogram that was not as well-defined as the one for the soft soils. (c) Neither the soft soil, nor the combined soft/intermediate soils showed any discernable lateral correlations. (d) In the absence of lateral discernable correlations, the lateral extent of the soft soils and the combined soft/intermediate soils was approximated to be less than the average borehole spacing

which is about 35 ft. The above results were also confirmed using the SPT data in the Santee Formation, as discussed in the following section.

3.1.3 SOFT ZONES CATEGORICAL VARIOGRAM ANALYSIS (SPT DATA)

The available SPT data in the Santee Formation were also converted into categorical data. For this purpose measured $(N_1)_{60}$ values in the Santee Formation were categorized into three groups as:

- (1) Soft soil ($(N_1)_{60}$ values less than or equal to 5),
- (2) Intermediate soil ($(N_1)_{60}$ values between 5 and 10), and
- (3) Stiff soil ($(N_1)_{60}$ values greater than 10).

Despite the fact that SPT data were heavily noisy, omni-directional lateral variographies were conducted for the above categorical soft soil and stiff soil variables, as shown in Figures 3.1.23 and 3.1.24. Neither variograms displayed any discernable lateral correlation structures. These results were consistent with the results of the CPT data in the Santee Formation, as described in Section 3.1.2.

3.2 CPT ESTIMATION RESULTS

Based on the fitted variogram models listed in Table 3.1.1, the CPT data was used to generate interpolated values along the nodes of a predefined liquefaction and FLAC model for cross-section A-A' and B-B', as shown in Figure 1.2.1. The model nodal locations were provided by Dr. F. Ostadan of Bechtel. These interpolated cross-sections were subsequently used in the liquefaction and settlement analysis described in WSRC (1995). The estimated tip resistances were interpolated using a three-dimensional irregular grid kriging program with layer-specific variogram models. The

estimated tip resistance and friction ratio contour maps in section A-A' and B-B' are shown in Figures 3.2.1 and 3.2.4, respectively.

The above results reflect the multi-layer variability of the CPT tip resistance data. However, smoothing effects due to kriging are also reflected in these latter contour maps. These results also indicate that the estimated most of the low tip resistances are located in the Santee Formation, as shown Figures 3.2.1 and 3.2.2.

For assessing the reliability of kriging estimated values, two separate cross-validations were performed. For this purpose, SCPT-1 and SCPT-6B were selected as targeted boreholes. In the cross-validation process, each measured tip resistance value from the targeted borehole were first eliminated and then estimated based on the neighboring measured values and the fitted layer-specific lateral and vertical variogram models. The estimated CPT profiles at these locations was then compared with the actual data to qualitatively judge the performance of the kriging. The results are displayed in Figures 3.2.5 through 3.2.6. In these figures, each estimated profile is accompanied by its upper and lower 95% confidence levels with its measured values. These results showed that in almost all cases, the measured values of tip resistance fall within the confidence interval of the kriging estimated values. This implies two facts:

- (1) Kriging estimated values are reliable estimates of the in-situ borehole measurements, and
- (2) Kriging standard deviations are adequate measures for quantifying the accuracy of the estimated values.

Cross-validation results in Figures 3.2.5 and 3.2.6 are based on performing kriging layer-by-layer with the depths to the top of each layer defining the control surfaces for estimation. This method proved to give the best results and is more appropriate where faulting or other vertical discontinuities may exist in the data.

Although layer-by-layer kriging cannot predict the actual geometry of the layers, it will respect the pre-determined layering system, thus it will not use data from other layers in making point estimates and hence does not introduce any false heterogeneity or extra uncertainty into the point estimates.

4.0 GEOSTATISTICAL SIMULATION OF SHEAR WAVE DATA

Available shear wave data from nineteen boreholes were geostatistically analyzed. The location of the investigated boreholes are shown in Figure 4.0.1.

The analysis of shear wave data was initially analyzed by dividing the soil volume in the investigated area into seven different layers as: Fill, TR1, TR2, TR3/TR4, DB1/DB4, DB5, and ST. However, unlike the CPT data, the shear wave velocity logs did not show strong evidences of layering and preliminary simulations yielded undue discontinuities along dividing surfaces of the various layers which ultimately produced unwanted and artificially high impedance contrasts for dynamic modeling. Therefore, in subsequent computations the entire profile was modelled as a single unit. Omni-directional lateral and vertical variograms were then computed and modeled, as shown in Figures 4.0.2 and 4.0.3. The vertical variogram displayed a particularly well defined spatial structure with a range of approximately 70 ft. Such a range is much larger than the typical 2 to 12 ft vertical ranges of CPT tip resistance values and shows that the shear wave velocity is much more continuous and homogeneous in the vertical direction.

4.1 SHEAR WAVE SIMULATION RESULTS

Shear wave values were simulated using sequential Gaussian simulation (sGs). For this purpose, fitted variogram models shown in Figures 4.0.2 through 4.0.3 were utilized. As noted above, due to excessive fluctuations in the multi-layer simulated shear wave profiles, a single-layer three-dimensional simulation was used.

In this process each simulated point is generated sequentially according to its normal conditional cumulative distribution function (ccdf) which is fully characterized through kriging system. Simulated values are conditioned on all original in-situ

measurements and all previously simulated values within their neighborhoods. In each simulation a seed number must be defined which determines the random path of the sequential simulation.

Shear wave values were simulated at centers of the four ITP tanks which are located at (62618.00', 70825.00'), (62750.00', 70825.00'), (62618.00', 70925.00'), and (62750.00', 70925.00'), as shown in Figure 1.2.1. Figures 4.1.1 through 4.1.4 display samples of simulated shear wave profiles at the center of various tanks. Each profile can be viewed as an equally likely realization of the shear wave values. The comparison of these figures with Figure 4.1.5 (i.e., the composite graph of measured shear wave velocities) clearly indicates that each simulated profile preserves the spatial variabilities exhibited by the original values.

5.0 GEOSTATISTICAL ANALYSIS OF SPT DATA

The conditional probability of liquefaction model used to evaluate the liquefaction hazard at ITP (Liao, 1986; WSRC, 1995) requires the normalized SPT blow count, $(N_1)_{60}$, as a measure of the soil's resistance to liquefaction. Available borings and penetrations at the ITP facility include SPT borings drilled by WSRC as part of the seismic qualification of ITP and by the consulting firm of Mueser-Rutledge during the original foundation investigations (WSRC, 1995). Four SPT boreholes were continuously split - spoon sampled by WSRC: H-SPT-14, H-SPT-18, H-SPT-20, and H-BOR-23.3. However, because of numerous underground interferences, none of these recent borings were drilled in close proximity to the ITP tanks, but were instead located around the perimeter of the ITP facility (Figure 1.2.1). These WSRC boreholes were completed under a rigorous quality assurance program, which include prior measurement of the energy delivered to the SPT hammer. The hammer energy ratio measured by WSRC was approximately 60 percent of the theoretical maximum. Other SPT borings completed by Mueser include all borings beginning with a "241 - 12 H" prefix in Figure 1.2.1. Eight of these Mueser borings are located within the footprint the ITP tanks, which make the use of these data highly desirable for defining the subsurface conditions directly beneath the tanks. However, the direct use of the Mueser SPT data is not acceptable for liquefaction analyses unless some rational method is employed to adjust the N values to $(N_1)_{60}$. Unfortunately, the hammer efficiency was not measured for the Mueser investigation, so other means had to be sought.

To incorporate the Mueser SPT N values in the hazard analysis, an estimate of the hammer efficiency was needed. A statistical review of N values at ITP by WSRC showed that Mueser's SPT N values are 1.6 times greater, on average, than those of WSRC in the layer of most interest for liquefaction analysis (i.e., TR3 / TR4). This suggest that Mueser's hammer was less efficient than that of WSRC and had an hammer energy ratio of about 37.5 percent (i.e., $60\% / 1.6 = 37.5$ percent). Hence

prior to simulation, all Mueser N values were divided by 1.6 to convert these N to $(N_1)_{60}$ values. Subsequently, all $(N_1)_{60}$ values from Mueser and WSRC were normalized to $(N_1)_{60}$ to complete the liquefaction analysis.

In addition to the SPT data, several CPT penetrations are also available near the ITP tanks (Figure 1.2.1). However, the use of CPT data is also problematic, because the probabilistic liquefaction model requires $(N_1)_{60}$ values as input (WSRC, 1995). To convert CPT data to SPT $(N_1)_{60}$ values, layer-specific regression analyses were performed by WSRC for paired CPT and SPT boreholes from the ITP and RTF geotechnical investigations. To pair the data, CPT data were averaged through a 2-foot interval starting 0.5 feet above the adjacent 1 1/2-foot sampling interval in the adjacent SPT boring. The general form of the regression model used is:

$$q_{c1} / N_1 = \beta_1 q_{c1} + \beta_2 fr + \beta_3 pp + \beta_4 p_o' + \beta_5 q_{c1} fr + \beta_6 q_{c1} pp + \beta_7 q_{c1} p_o' + \beta_8 fr pp + \beta_9 fr p_o' + \beta_{10} pp p_o'$$

where: q_{c1} = CPT tip resistance normalized to 1 tsf,
 fr = CPT friction ratio;
 pp = CPT pore pressure in tsf
 p_o' = effective overburden pressure in tsf.

The results of the regression analysis are given below.

layer	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}
TR1	0.0194	0.654	-0.206	2.41	-0.00454	0.00031	0.0103	0.0165	-0.557	0.031
TR2(a)	0.111	4.32	-14.7	3.73	-0.0286	-0.0918	-0.0929	6.45	0	25.7
TR2(b)	0.0496	-3.69	-2.27	4.06	0.0215	0.0351	-0.0357	1.04	1.09	-0.397
TR3/TR4	-0.0410	0.380	0.211	2.33	0.0108	-0.0297	0.0423	0.0714	-0.398	-0.060
DB1/DB3	0.116	6.13	-5.62	5.06	-0.0071	0.0232	-0.0586	1.34	-3.90	0.809
DB4	0.0480	0.77	-0.545	1.93	0.0450	0.00521	-0.0206	0.137	-0.899	0.0284
DB5	0.501	-7.37	0.272	-0.140	-0.0670	-0.00175	-0.0772	-0.0006	2.27	-0.0824
ST	-0.0651	3.34	-0.215	0.697	0.0195	0.00220	0.0196	0.0062	-0.918	0.017

TR2(a) = TR2 layer above the water-table

TR2(b) = TR2 layer below the water-table.

The regression analyses and analysis of variance tables are included in Appendix VI.

The above measured, corrected and regressed $(N_1)_{60}$ simulated N values were subjected to multi-layer lateral and vertical variography. The entire process was conducted through ResMod. For three-dimensional sequential Gaussian simulation the entire data set was normally transformed. The fitted variogram parameters of the normal score data are shown in Table 5.0.1.

Given the normal transformation of data, most variograms have sill values close to unity. The ranges, however, are very similar to other investigated CPT data. The vertical ranges vary from 2 to 13 ft, while lateral ranges vary from 300 to 450 ft. Three layer groups, i.e. TR2 above water table, TR3/TR4, and the Santee Formation, display no discernable lateral correlational structure.

5.1 SPT ESTIMATION AND SIMULATION RESULTS

Estimated and simulated $(N_1)_{60}$ values were generated using three-dimensional kriging and sequential Gaussian simulation techniques using the data described in Section 5.0. The fitted variogram models, listed in Table 5.0.1, were utilized.

The SPT data were used to generate estimated maps based on the kriging technique. As a sample, the estimation results in an east-west cross-section at Northing = 70590.00 ft, as well as one lateral cross section in sub-layers of DB1/DB3 are displayed in Figures 5.1.1 through 5.1.2.

Upon completion of the kriging exercise, the sequential Gaussian simulation of $(N_1)_{60}$ values was conducted. As a sample, the same cross sections as above are used to display the simulation results, as shown in Figures 5.1.3 through 5.1.4.

The comparison of the above two sets of results highlights the differences between the kriging and simulation outputs. The kriging surfaces, Figures 5.1.1 and 5.1.2, displayed a smooth characteristic. Smoothing becomes specially excessive in sparsely sampled locations, such as the southwest corners of Figure 5.1.2. The simulated surfaces, on the other hand, preserved the variability of the investigated N values, as shown in Figures 5.1.3 and 5.1.4. These results indicated that as data become sparse the use of simulated results are more advantageous.

Comparison of vertical cross sections (Figures 5.1.1 and 5.1.3) also proves that simulation procedures preserve both inter- and intra-layered variabilities. Such variabilities are absent in kriging results, such as Figure 5.1.1. Also, to check if the simulation is reasonable, the simulated results at the 4 nodes nearest to the centerpoints of the ITP tanks are plotted against the nearby WSRC SPT N data (Figure 5.1.5). The simulated results show reasonable agreement with the nearby data in the zone of interest for liquefaction analyses (i.e., between elevations 275 and 230 feet

MSL. The real and simulated data from this interval were subsequently used in the probabilistic liquefaction hazard evaluation (WSRC, 1995).

6.0 SUMMARY

The geostatistical analyses of the in-situ borehole measurements from the ITP site revealed the following conclusions:

1. **Borehole Data Structure:** The borehole data structure displayed a number of distinct characteristics. First, the three-dimensional data resolution was highly imbalance, with very tight resolution in the vertical direction and orders of magnitude wider resolutions in the lateral direction. Second, the geological formation clearly exhibited a multi-layer stratigraphy with differing features. Based on these distinct features, each borehole data was divided into a number of substrata by the geological and geotechnical staff at WSRC. Third, the preliminary stratigraphic model of the site showed a non-horizontal, layered structure with potential faults or other vertical discontinuities.
2. **Complicated Intra-layer Variations:** Despite the initial grouping of the borehole data into a number of substrata, in-situ measurements within each layer displayed complicated vertical and lateral variations . These variations, however, were only partially explainable based on deterministic geological and geotechnical models. Therefore, the use of statistical methods became inevitable.
3. **Suitable Statistical Tool:** Among statistical methods, geostatistical algorithms appeared to be the most suitable due to a number of reasons. First, geostatistics recognizes the multi-layer, three-dimensional structure of the borehole data. Second, unlike classical statistical procedures, geostatistics incorporates the potential spatial (auto-correlational) structure of the collected data. Third, vertically clustered borehole measurements can be processed by geostatistical methods. Finally, geostatistics offers both estimation and simulation procedures that can be used in a variety of applications.

4. **CPT Variography and Estimation Results:** The variography along the vertical direction revealed well defined layers or beds with ranges varying between 2 to 12 ft. The results of the omni-directional lateral variograms revealed more complicated structures than the vertical variograms. The lateral ranges of different layers varied from 40 to 130 ft. Among the exceptions was the Santee Formation that exhibited a lateral pure nugget effect. Estimated CPT results were generated for liquefaction and FLAC modeling purposes. These estimated values preserved the multi-layer structure of the investigated variables. However, in sparsely sampled locations have a tendency to generate smooth maps.
5. **Soft Zone Categorical Variography in the Santee Formation:** Measured tip resistances and N values in the Santee Formation were categorized into three groups as: Soft, Intermediate, and Stiff soils. Results indicated that: (a) The soft soils had an average thickness of less than 4 ft. (b) The average thickness of the combined soft/intermediate soils appeared to be less than 8 ft. The combined soft/intermediate soils had a vertical variogram that was not as well-defined as the one for the soft soils. (c) Neither the soft soil, nor the combined soft/intermediate soils showed any discernable lateral correlations. (d) In the absence of lateral discernable correlations, the lateral extent of the soft soils and the combined soft/intermediate soils was approximated to be less than 35 ft.
6. **Shear Wave Variography and Simulation Results:** The analysis of shear wave data was initiated by dividing the soil volume in the investigated area into seven different layers as: Fill, TR1, TR2, TR3/TR4, DB1/DB4, DB5, and ST. This approach, however, yielded undue discontinuities along dividing surfaces of the various layers. Therefore, in subsequent computations the entire formation was considered as a single unit. Simulated results indicated that each simulated

profile preserved the spatial variabilities exhibited by the original values.

7. **SPT Variography Results:** Geostatistically simulated and estimated $(N_1)_{60}$ values were generated using three-dimensional kriging and sequential Gaussian simulation techniques. The comparison of the above two sets of results indicated that: (a) the kriging surfaces display a smooth characteristic which becomes specially excessive in sparsely sampled locations, and (b) the simulation procedures preserve both inter- and intra-layered variabilities.

7.0 REFERENCES

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Appendix I

Tables

Table 1.2.1 List of Geological Substrata at the ITP Site

Layer	Description
Fill	Fill
TR1	Tobacco Road 1
TR2	Tobacco Road 2
TR3	Tobacco Road 3
TR4	Tobacco Road 4
DB1	Dry Branch 1
DB2	Dry Branch 2
DB3	Dry Branch 3
DB4	Dry Branch 4
DB5	Dry Branch 5
ST	Santee Formation

Table 3.0.1 List of Investigated CPT Borehole Data

Borehole ID No.	Easting (ft)	Northing (ft)	Surface Elevation (ft)
SCPT-01	62532.00	70843.97	326.38
SCPT-5	62667.40	70797.30	326.08
SCPT-6B	62783.01	70903.41	328.17
CPT-7	62612.85	71030.17	328.76
SCPT-10	62554.29	71002.02	328.41
CPT-11	62767.43	70885.10	328.03
SCPT-14	62375.16	70935.99	300.09
CPT-16	62426.06	70733.84	297.57
SCPT-18	62657.50	70601.00	298.32
SCPT-20	63059.62	70843.86	204.29
SCPT-20.1	63051.50	70835.00	294.31
SCPT-20.2	63076.50	70848.00	294.11
SCPT-23	63017.30	70970.68	296.59
CPT-25	62998.40	71197.74	296.20
CPT-26	62805.00	70764.00	326.13
SCPT28.2	62908.00	70611.74	300.42
CPT-28	62879.94	70611.74	300.56
CPT-29	62681.30	71113.00	334.43
CPT-30	62805.00	70989.00	328.49
CPT-31	62537.00	70785.00	326.08

Table 3.0.2 List of Removed Negative Friction Ratio Data

Borehole	Interval or Elevation	Layer	Comment
SCPT6B	286.09-279.35	TR1	All negative FR values
SCPT01	315.07	Fill	FR = -473.22
SCPT01	310.09	Fill	FR = -7.81
SCPT01	271.18	TR1	FR = -443.21
SCPT01	279.60	TR1	FR = -19.26
SCPT14	254.96	TR2	FR = -82.97
SCPT14	254.95	TR2	FR = -83.18
SCPT14	254.95	TR2	FR = -83.68
SCPT20-1	286.53	Fill	FR = -80.54

Table 3.0.3 Locations with Slightly Negative Tip Resistances

Borehole	Elevation	Tip resistance	Friction Ratio	Layer
CPT-11	316.16	-2.46	-58	Fill
CPT-11	294.82	-.6	-376	Fill
SCPT05	312.22	-17.74	-18	Fill
SCPT05	300.03	-16.97	-9	Fill
SCPT10	313.19	-5.18	-25	Fill
SCPT10	313.12	-5.05	-25	Fill
SCPT10	313.05	-6.41	-20	Fill
SCPT10	312.98	-7.27	-20	Fill
SCPT10	312.90	-6.41	-30	Fill
SCPT10	305.99	-18.46	-23	Fill
SCPT10	304.76	-1.66	-92	Fill
SCPT10	304.69	-3.62	-43	Fill
SCPT10	304.61	-3.62	-49	Fill
SCPT10	299.36	-.77	-184	Fill
SCPT10	298.10	-29.61	-8.3	Fill
SCPT20-2	286.36	-.23	-26	Fill
SCPT20-2	286.29	-.11	-167	Fill
SCPT6B	306.06	-27.02	-9.5	Fill

Table 3.0.4 List of Removed Spurious Data in the Fill Layer

Borehole	Interval	Layer
SCPT01	326.83 - 320.75	Fill
SCPT05	326.09 - 320.06	Fill
SCPT05	385.25 - 218.75	TR1
SCPT6B	328.17 - 322.75	Fill
CPT-7	328.76 - 322.80	Fill
SCPT10	328.41 - 319.90	Fill
CPT-11	327.87 - 321.78	Fill
SCPT18	298.32 - 292.23	Fill
SCPT20-1	294.31 - 288.53	Fill
SCPT20-2	294.11 - 286.11	Fill
SCPT23	296.59 - 289.50	Fill
CPT-26	326.13 - 320.02	Fill
CPT28	300.56 - 294.45	Fill
SCPT28-2	300.42 - 294.25	Fill
CPT-29	334.43 - 328.01	Fill
CPT-30	328.49 - 322.48	Fill
CPT-31	326.08 - 319.95	Fill

Table 3.0.5 List of Removed High Friction Ratio Data

Borehole	Elevation	qc	fs	FR	layer
SCPT1	314.82	.8	1.59	198	Fill
SCPT1	288.59	3.27	1.58	48.4	Fill
SCPT1	288.51	1.54	1.53	99.3	Fill
SCPT1	288.43	1.07	1.39	130	Fill
SCPT1	288.36	3.07	1.74	56.7	Fill
SCPT05	315.53	.38	1.21	315	Fill
SCPT10	312.83	.47	2.32	490	Fill
SCPT10	304.54	1.61	2.17	135	Fill
SCPT10	299.50	2.63	1.92	72.8	Fill
SCPT10	299.43	.62	1.78	288	Fill
SCPT10	299.29	.11	1.43	1253	Fill
SCPT10	299.21	3.24	1.922	59.3	Fill
SCPT23	293.16	0	0	161	Fill
SCPT23	293.08	0	0	65.5	Fill
SCPT28-2	294.60	.22	.12	52.8	Fill
SCPT28-2	294.53	.33	.75	224	Fill
SCPT28-2	294.46	1.89	1.2	63.4	Fill
SCPT6B	327.20	0	0	92.5	Fill

Table 3.1.1 Parameters of Fitted Multi-Layer Variograms of Tip Resistances

	Lateral Variogram			Vertical Variogram		
Layer	Nugget	Range	Sill	Nugget	Range	Sill
Fill	---	130	410	---	2	410
TR1	650	0	0	---	2	650
TR2	---	120	1800	---	6	1800
TR3	---	120	500	---	6	500
TR4	420	0	0	---	3	420
DB1	---	50	4000	---	12	4000
DB2	---	75	1700	---	4	1700
DB3	---	110	900	---	8	9000
DB4	100	0	0	---	4	1000
DB5	---	40	1000	---	1	1000
ST	8000	0	0	---	6	8000

Table 5.0.1 Parameters of Fitted Multi-Layer Normal Score Variograms of N Values

	Lateral Variogram			Vertical Variogram		
Layer	Nugget	Range	Sill	Nugget	Range	Sill
TR1	---	400	1.3	0.022	13	0.255
TR2A	1	---	---	0	4	0.7
TR2B	0.5	450	0.6	0	2	0.42
TR3/TR4	1	---	---	0.055	4	0.07
DB1/DB3	0.7	400	0.46	0.050	4	0.045
DB4	---	300	1.1	0.070	2	0.2
DB5	---	350	1.1	0	5.3	0.4
ST	1	---	---	0.320	5	0.3

Appendix II

Figures

Lateral & Vertical Variogram of Tip Fill Layer

----- Lateral variogram — Vertical Variogram

(* = Sample Lateral Variograms)

Figure 3.1.1 Lateral and Vertical Variogram of Tip Resistance (Fill Layer)

Lateral & Vertical Variogram of Tip TR1 Layer

Figure 3.1.2 Lateral and Vertical Variogram of Tip Resistance (TR1 Layer)

Lateral & Vertical Variogram of Tip TR2 Layer

..... Lateral Variogram — Lateral Variogram

(* = Sample Lateral Variograms)

Figure 3.1.3 Lateral and Vertical Variogram of Tip Resistance (TR2 Layer)

Lateral & Vertical Variogram of Tip TR3 Layer

(* = Sample Lateral Variograms)

Figure 3.1.4 Lateral and Vertical Variogram of Tip Resistance (TR3 Layer)

Lateral & Vertical Variogram of Tip TR4 Layer

(* = Sample Lateral Variograms)

Figure 3.1.5 Lateral and Vertical Variogram of Tip Resistance (TR4 Layer)

Lateral & Vertical Variogram of Tip DB1 Layer

(* = Sample Lateral Variograms)

Figure 3.1.6 Lateral and Vertical Variogram of Tip Resistance (DB1 Layer)

Lateral & Vertical Variogram of Tip DB2 Layer

(* = Sample Lateral Variograms)

Figure 3.1.7 Lateral and Vertical Variogram of Tip Resistance (DB2 Layer)

Lateral & Vertical Variogram of Tip DB3 Layer

(* = Sample Lateral Variograms)

Figure 3.1.8 Lateral and Vertical Variogram of Tip Resistance (DB3/DB4 Layer)

Lateral & Vertical Variogram of Tip DB5 Layer

(* = Sample Lateral Variograms)

Figure 3.1.9 Lateral and Vertical Variogram of Tip Resistance (DB5 Layer)

Lateral & Vertical Variogram of Tip Santee Layer

(* = Sample Lateral Variograms)

Figure 3.1.10 Lateral and Vertical Variogram of Tip Resistance (Santee Layer)

Figure 3.1.11 Lateral and Vertical Variogram of Tip Resistance (Soft Soil)

Lateral & Vertical Variogram Intermediate Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.12 Lateral and Vertical Variogram of Tip Resistance (Intermediate Soil)

Lateral & Vertical Variogram Stiff Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.13 Lateral and Vertical Variogram of Tip Resistance (Stiff Soil)

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.14 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 30° (Soft Soil)

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.15 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 45° (Soft Soil)

Lateral & Vertical Variogram (60)
Soft Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.16 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 60° (Soft Soil)

Lateral & Vertical Variogram (30)

Intermediate Soil

* = Sample Lateral Variograms
 x = Sample Vertical Variograms

Figure 3.1.17 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 30°(Intermediate Soil)

Lateral & Vertical Variogram (45)

Intermediate Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.18 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 45°(Intermediate Soil)

Lateral & Vertical Variogram (60)

Intermediate Soil

* = Sample Lateral Variograms
 x = Sample Vertical Variograms

Figure 3.1.19 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 60°(Intermediate Soil)

Lateral & Vertical Variogram (30)

Stiff Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.20 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 30°(Stiff Soil)

Lateral & Vertical Variogram (45)

Stiff Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.21 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 45°(Stiff Soil)

Lateral Variogram (60 degree) Stiff Soil

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.22 Vertical and Directional Lateral Variogram of Tip Resistance along Angle 60°(Stiff Soil)

* Lateral Variogram — Vertical Variogram

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.23 Lateral and Vertical Variogram (Indicator #1)

* = Sample Lateral Variograms
x = Sample Vertical Variograms

Figure 3.1.24 Lateral and Vertical Variogram (Indicator #2)

Contour Map of Tip Resistance Section A-A'

Figure 3.2.1 Kriging Map of Tip Resistance along Cross-Section A-A'

Contour Map of Tip Resistance Section B-B'

Figure 3.2.2 Kriging Map of Tip Resistance along Cross-Section B-B'

Contour Map of Fraction Ratio Section A-A'

Figure 3.2.3 Kriging Map of Fraction Ratio along Cross-Section A-A'

Contour Map of Fraction Ratio Section B-B'

Figure 3.2.4 Kriging Map of Fraction Ratio along Cross-Section B-B'

Vertical Distribution of q_c at scpt1 (Cross Validation)

Figure 3.2.5 Cross-Validation Results at SCPT1 (Using within-layer-depth)

Vertical Distribution of q_c at scpt6b (Cross Validation)

Figure 3.2.6 Cross-Validation Results at SCPT6B (Using within-layer-depth)

Figure 4.0.1 Locations of Investigated CPT Boreholes

Figure 4.0.2 Omni-Directional Lateral Variogram of Shear Wave Data

Figure 4.0.3 Omni-Directional Vertical Variogram of Shear Wave Data

Vertical Shear Wave Velocity at (62618, 70825)

Figure 4.1.1 Simulated Shear Wave Velocity Profile using Seed #1 at (62618', 70825')

Vertical Shear Wave Velocity at (62750, 70825)

Figure 4.1.2 Simulated Shear Wave Velocity Profile using Seed #1 at (62750', 70825')

Vertical Shear Wave Velocity at (62618, 70952)

Figure 4.1.3 Simulated Shear Wave Velocity Profile using Seed #1 at (62618', 70952')

Vertical Shear Wave Velocity at (62750, 70952)

Figure 4.1.4 Simulated Shear Wave Velocity Profile using Seed #1 at (62750', 70952')

Figure 4.1.5 ITP Shear Wave Velocity from SCPT

Figure 5.0.1 Locations of Combined SPT and CPT-Based Boreholes

Cross-section Display
Kriging 3 of 30

Figure 5.1.1 Kriging Map along the East-West Cross-Section at Northing = 70590'

Figure 5.1.2 Kriging Map along a Lateral Sub-Layer at DB1/DB3

Cross-section Display

sGs 3 of 30

Figure 5.1.3 Simulated Map along the East-West Cross-Section
at Northing = 70590'

Figure 5.1.4 Simulated Map along a Lateral Sub-Layer at DB1/DB3

ITP Real and Simulated Data

Figure 5.1.5 ITP Real and Simulated Data

Appendix III

Preliminary Evaluation of OCR from SCPT Data by P. W. Mayne

FAX Memorandum

Date: April 15, 1994

To: Mike Lewis
Geotechnical Engineering Manager
SRS/Bechtel, Savannah River Inc.
802 E. Martintown Road, BTC-416
North Augusta, SC 29841

FAX: 7 pages to 803-952-5183

From: Paul W. Mayne, Associate Professor, CE

Re: Preliminary Evaluation of OCR from Piezocone SCPT-18 at SRS-H Area ITP

Dear Mike,

Enclosed is a preliminary assessment of OCR solely using the piezocone data from one of the soundings at the ITP site. This particular sounding was chosen at random as representative of site conditions, however, it is located downhill and south of the tank area. Using pre-established analysis procedures, we evaluated the OCR profiles in this manner:

1. Initially, the sounding was divided into (a) clay and (b) sand layers based on visual examination of the q_c , f_s , and u_{bt} data. We understand that q_c is supposed to represent the corrected cone tip resistance, q_T .
2. For clay layers, we evaluated the effective preconsolidation stress using the following relationship (Mayne and Holtz, 1988; Kulhawy and Mayne, 1990):

$$[1] \quad \sigma_p' = 0.54 \Delta u_2$$

where $\Delta u_2 = \Delta u_{bt}$ = measured excess pore pressure behind the cone tip.

The OCR for clay layers was then calculated as $OCR = \sigma_p' / \sigma_{vo}'$ where the effective overburden pressure (σ_{vo}') was preliminarily evaluated assuming a total unit weight $\gamma = 115$ pcf throughout the profile and groundwater taken to be hydrostatic below a depth of 25 feet.

3. Values of K_0 in the clay were evaluated according to an expression derived from regression analysis of self-boring pressuremeter test (SBPMT) data compiled from 56 different clays (Mayne and Kulhawy, 1990):

4. In the sand layer, the estimate of OCR is more difficult because of the paucity of stress history measurements in natural sands. A methodology based on CPT-calibration chamber data on clean sands has therefore been used (Mayne and Kulhawy, 1991). For this procedure, it is necessary to solve two simultaneous equations or iterate to find both K_o and OCR:

$$[3] \quad K_o = (\sigma_{ho}' / \sigma_{vo}') = \frac{(p_s / \sigma_{vo}') (q_c / p_s)^{1.6}}{145 \exp \left\{ \left[\frac{(q_c / p_s) / (\sigma_{vo}' / p_s)^{0.5}}{12.2 OCR^{0.18}} \right]^{0.5} \right\}}$$

$$[4] \quad K_o = (1 - \sin \phi') OCR^{\sin \phi'}$$

Equation [3] is derived from a statistical analysis of corrected CPT data from 24 different sets of calibration chamber tests on unaged, uncemented, quartzitic sands. It is noted that the data are primarily from clean sands. Equation [4] is based on laboratory triaxial and oedometer measurements on 171 different soils, including sands, gravels, silts, and clays (Mayne and Kulhawy, 1982). The use of [4] also requires an assessment of the effective friction angle of the material (ϕ') for which the relationship proposed by Robertson and Campanella (1983) has been adopted:

$$[5] \quad \phi' = \arctan[0.10 + 0.38 \log(q_c / \sigma_{vo}')]]$$

Derived profiles of OCR, K_o , σ_p' , and ϕ' (sand) are shown on the enclosed figures. The magnitudes of stress history (OCR and σ_p') appear to be generally consistent with the results of laboratory oedometer tests on clay and sandy clay layers conducted by Law Engineering and recently provided to us in summarized tables and graphs. In the vicinity of SCPT-18, only a few OCR estimates from DMT soundings were available and these also appear compatible with the preliminary interpretations of piezocone data.

We should like to further discuss these preliminary evaluations with at your convenience. In particular, we are curious to know more details on the correction of q_r values, since this data may also be used to derive profiles of σ_p' , OCR, K_o , and effective stress angle (ϕ') in clays. In addition, while the sand strata at the ITP site appear to have only about 10 to 15 percent fines, the fines content appears gap-graded with high-plasticity clay-size particles. This may affect the interpretation of CPT data in the sand strata.

Sincerely,

Paul W. Mayne

Paul W. Mayne, PhD, P.E.
Associate Professor

(404) 894-6226

REFERENCES

- Kulhawy, F.H. and Mayne, P.W. (1990). Manual on Estimating Soil Properties for Foundation Design. *Report EL-6800*, Electric Power Research Institute, Palo Alto, 306 p.
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- Mayne, P.W. and Kulhawy, F.H. (1982). K_o -OCR Relationships in Soil. *Journal of the Geotechnical Engineering Division*, ASCE, 108 (GT6), 851-872.
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- Robertson, P.K. and Campanella, R.G. (1983). Interpretation of Cone Penetration Tests. Part 1: Sands. *Canadian Geotechnical Journal* 20 (4), 718-733.

SRS-H Area-ITP-SCPT18

SRS-H Area-ITP-SCPT18

SRS-H Area-ITP-SCPT18

• Effect. vl. stress — Precons. stress

SRS-H Area-ITP-SCPT18

May 6, 1994

Mike Lewis
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802 E. Martintown Road, BTC-416
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404•894•2201
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Re: (1) Excel File with K_o -OCR Data Reduction from SCPT-18
(2) Correlative Estimate of V_s from CPT-23- q_c Profile

Dear Mike,

Here is the floppy disk file of the reduced OCR data. I believe Yasser Hegazy left the file unfiltered; that is, there are spikes in the transition zones between alternating clay and sand strata. The procedures for the OCR and K_o evaluations were provided to you in a previous memo. We also attempted an estimate of shear wave velocity (V_s) and low-amplitude shear modulus (G_{max}) from the cone tip resistance measurements at CPT-23. These were made using the following:

Sands: $V_s = 277 (q_c)^{0.13} (\sigma_{vo}')^{0.27}$ (Baldi et al., 1989)

where V_s is in m/sec and q_c and σ_{vo}' are in MPa.

Sands: $G_{max} = 1634 (q_c)^{0.250} (\sigma_{vo}')^{0.375}$ (Rix and Stokoe, 1991)

where all stresses are in units of kPa.

Clays: $V_s = 126 [\log[q_c/(p_a \sqrt{PI})] + 1]$ (Mayne & Rix, 1993)

where V_s is in m/sec, PI = plasticity index in percent, q_c and p_a are in same units, and $p_a = 1 \text{ atm} \approx 100 \text{ kPa}$.

Clays: $G_{max} = 406 (q_c)^{0.695} (e_o)^{-1.130}$ (Mayne & Rix, 1993)

with G_{max} and q_c in kPa and e_o is dimensionless.

Should you have any questions regarding these items, please call.

Sincerely,

Paul W. Mayne, PhD, P.E.
Associate Professor

OFF: (404) 894-6226

FAX: (404) 894-2281

xc: S. Rouhani

SRS-H Area-ITP-SCPT-23

SRS-H Area-ITP-SCPT-23

SRS-H Area-ITP-SCPT-23

Appendix IV

List of SCPT Borehole Logs

SCPT-01

APPLIED RESEARCH ASSOCIATES, INC.

01/30/93

North 70843.97

East 62532.00

Elevation 326.83

SCPT-01

APPLIED RESEARCH ASSOCIATES, INC.

01/30/93

North 70843.97

East 62532.00

Elevation 326.83

SCTP-5

APPLIED RESEARCH ASSOCIATES, INC.

02/24/93

North 70797.30

East 62667.40

Elevation 326.08

SCTP-5

APPLIED RESEARCH ASSOCIATES, INC.

02/24/93

North 70797.30

East 62667.40

Elevation 326.08

SCPT-6B

APPLIED RESEARCH ASSOCIATES, INC.

02/22/93

North 70903.41

East 62783.01

Elevation 328.17

CPT-7

APPLIED RESEARCH ASSOCIATES, INC.

04/15/93

North 71030.17

East 62612.85

Elevation 328.76

SCPT-10

APPLIED RESEARCH ASSOCIATES, INC.

02/01/93

North 71002.02

East 62554.29

Elevation 328.41

CPT 11
~~CPT 11~~

APPLIED RESEARCH ASSOCIATES, INC.

01/30/93

North 70885.10

East 62767.43

Elevation 327.87

SCPT-14

APPLIED RESEARCH ASSOCIATES, INC.

01/29/93

North 70935.99

East 82375.16

Elevation 300.09

CPT-16

APPLIED RESEARCH ASSOCIATES, INC.

04/21/93

North 70733.84

East 62426.06 -

Elevation 297.57

SCPT-18

APPLIED RESEARCH ASSOCIATES, INC.

01/27/93

North 70601.00

East 62657.50

Elevation 298.32

SCPT-20

APPLIED RESEARCH ASSOCIATES, INC.

01/26/93

North 70843.86

East 63059.62

Elevation 204.29

SCTP-20.1

APPLIED RESEARCH ASSOCIATES, INC.

02/24/93

North 70835.00

East 63051.50

Elevation 294.31

SCPT-23

APPLIED RESEARCH ASSOCIATES, INC.

03/06/93

North 70970.68

East 63017.30

Elevation 296.59

CPT-25

APPLIED RESEARCH ASSOCIATES, INC.

05/24/93

North 71197.74

East 62998.40

Elevation 296.20

CPT-26

APPLIED RESEARCH ASSOCIATES, INC.

08/23/93

North 70764.00

East 62805.00 -

Elevation 326.13

SCTP-28.2

APPLIED RESEARCH ASSOCIATES, INC.

02/25/93

North 70611.74

East 62908.00

Elevation 300.42

CPT-28

APPLIED RESEARCH ASSOCIATES, INC.

01/28/93

North 70611.74

East 62897.94

Elevation 300.56

Note: loss
of tip
resistance
in TR2

North 71113.00

East 62681.30

Elevation 334.43

CPT-31

APPLIED RESEARCH ASSOCIATES, INC.

04/20/93

North 70785.00

East 62537.00

Elevation 326.08

Appendix V

List of Input Data Files

LIST OF INPUT DATA FILES
(Provided by WSRC)

File name	Description
SCPT.ZIP	This zip-file includes 11 files which are SCPT01.ECG, SCPT05.ECG, SCPT10.ECG, SCPT14.ECG, SCPT18.ECG, SCPT20.ECG, SCPT201.ECG, SCPT202.ECG, SCPT23.ECG, SCPT282.ECG, and SCPT6B.ECG. These files includes Measurement Borehole ID, Northing, Easting, Surface Elevation, Depth, Elevation, Sleeve Stress, Tip Stress Uncorrected (UNC), Tip Stress Corrected (COR), Ratio COR, Pore Pressure, Overburden, Effective Overburden, Wet Density, Relative Density, Classification, and Blow Count.
CPT.ZIP	This zip-file includes 15 files which are CPT11.ECG, CPT16.ECG, CPT25.ECG, CPT26.ECG, CPT28.ECG, CPT29.ECG, CPT30.ECG, CPT31.ECG, CPT32.ECG, CPT32B.ECG, CPT34.ECG, CPT27.ECG, CPT38.ECG, CPT7.ECG, and CPT-11.ECG. These files includes Borehole ID, Northing, Easting, Surface Elevation, Depth, Elevation, Sleeve Stress, Tip Stress UNC, Tip Stress COR, Ratio COR, Pore Pressure, Overburden, Effective Overburden, Wet Density, Relative Density, Classification, and Blow Count.
ITPCPT1.ZIP	This is a zip-file of ITPCPT1.DBF. It includes Depth, Elevation, Sleeve Stress, Tip Stress UNC, Tip Stress COR, Ratio, Pore

Pressure, Total Pressure, Effective Overburden, Wet Density, Relative Density, Classification, Blow Count, and Borehole ID Number.

ITPCPT2.ZIP This is a zip-file of ITPCPT2.DBF. It includes Depth, Elevation, Sleeve Stress, Tip Stress UNC, Tip Stress COR, Ratio, Pore Pressure, Total Pressure, Effective Overburden, Wet Density, Relative Density, Classification, Blow Count, and Borehole ID Number.

ITPCPT3.ZIP This is a zip-file of ITPCPT3.DBF. It includes Depth, Elevation, Sleeve Stress, Tip Stress UNC, Tip Stress COR, Ratio, Pore Pressure, Total Pressure, Effective Overburden, Wet Density, Relative Density, Classification, Blow Count, and Borehole ID Number.

ITPSPT.DAT Borehole ID Number, Easting, Northing, Elevation, and Layer markers are listed in this file.

ITPA.ECG This file includes the coordinates of FLAC element centers of A-A' section.

ITPB.ECG This file includes the coordinates of FLAC element centers of B-B' section.

SWAVE.DAT This file includes Borehole ID Number, Elevation, Shear Wave, and Layer.

SWAVE.COR This file includes Northing, Easting, and Borehole ID Number.

SWAVE.STA The Shear Wave Velocity statistics is listed in this file.

SWAVE.LAY	The Layer Shear Wave Velocity statistics is listed in this file.
ITPSPT.DAT	This file includes Borehole ID Number, Easting, Northing, Elevation, Blow Count, Layer, and Category.
SR_ITP.DAT	This file includes Borehole ID Number, Elevation, Blow Count, and Layer.
N1SIM.DAT	This file includes Easting, Northing, Elevation, Computed Blow Count, Layer, and Borehole ID Number.

Appendix VI

Regression Analyses and Analysis of Variance

MTB > READ 'TR1.DAT' C1-C5
38 ROWS READ

ROW	C1	C2	C3	C4	C5
1	70.40	164.40	2.25	15.65	0.30
2	54.40	199.02	4.17	6.39	0.42
3	56.00	168.94	5.70	1.75	0.48
4	41.31	121.87	6.70	5.43	0.60

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

* NOTE * FR is highly correlated with other predictor variables

* NOTE * PP is highly correlated with other predictor variables

* NOTE * QC1xFR is highly correlated with other predictor variables

* NOTE * FRxPO is highly correlated with other predictor variables

* NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

QC1/N1 = 0.0194 QC1 + 0.654 FR - 0.206 PP + 2.41 PO - 0.00454 QC1xFR
+ 0.00031 QC1xPP + 0.0103 QC1xPO + 0.0165 FRxPP - 0.557 FRxPO
+ 0.031 PPxPO

*Final regression
equations*

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.019391	0.008288	2.34	0.027
FR	0.6535	0.3062	2.13	0.042
PP	-0.2063	0.2221	-0.93	0.361
PO	2.4058	0.5065	4.75	0.000
QC1xFR	-0.004543	0.002283	-1.99	0.056
QC1xPP	0.000314	0.001111	0.28	0.780
QC1xPO	0.010255	0.006897	1.49	0.148
FRxPP	0.01655	0.01171	1.41	0.169
FRxPO	-0.5565	0.1421	-3.92	0.001
PPxPO	0.0308	0.1075	0.29	0.776

s = 0.5138

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	279.012	27.901	105.69	0.000
Error	28	7.392	0.264		
Total	38	286.404			

SOURCE	DF	SEQ SS
QC1	1	198.009
FR	1	37.602
PP	1	2.241
PO	1	30.525
QC1xFR	1	0.306
QC1xPP	1	0.719
QC1xPO	1	0.110
FRxPP	1	0.621
FRxPO	1	8.857
PPxPO	1	0.022

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
1	164	2.3352	2.1351	0.4807	0.2002	1.10 X
37	0	0.0000	1.0104	0.2127	-1.0104	-2.16R
38	116	2.1288	3.0233	0.4025	-0.8945	-2.80R

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.912

MTB > WRITE 'TR1.OUT' C12 C99

MTB > READ 'TR2A.DAT' C1-C5

12 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	49.06	158.25	1.81	3.41	0.60
2	41.25	325.51	0.36	0.29	0.72
3	32.84	277.73	0.45	0.24	0.78
4	33.73	223.62	0.71	0.08	0.90

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

FRxPO is highly correlated with other X variables

FRxPO has been removed from the equation

NOTE * QC1 is highly correlated with other predictor variables
 NOTE * FR is highly correlated with other predictor variables
 NOTE * PP is highly correlated with other predictor variables
 NOTE * PO is highly correlated with other predictor variables
 NOTE * QC1xFR is highly correlated with other predictor variables
 NOTE * QC1xPP is highly correlated with other predictor variables
 NOTE * QC1xPO is highly correlated with other predictor variables
 NOTE * FRxPP is highly correlated with other predictor variables
 NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

C1/N1 = -0.111 QC1 + 4.32 FR - 14.7 PP + 3.73 PO - 0.0286 QC1xFR
 - 0.0918 QC1xPP - 0.0929 QC1xPO + 6.45 FRxPP + 25.7 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Constant				
C1	0.11058	0.05069	2.18	0.117
FR	4.325	5.664	0.76	0.501
PP	-14.74	13.91	-1.06	0.367
PO	3.732	8.239	0.45	0.681
C1xFR	-0.02856	0.02508	-1.14	0.338
C1xPP	-0.09184	0.05911	-1.55	0.218
C1xPO	-0.09294	0.08576	-1.08	0.358
FRxPP	6.449	5.323	1.21	0.312
PPxPO	25.75	34.82	0.74	0.513

= 0.8570

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	9	389.156	43.240	58.87	0.003
Error	3	2.203	0.734		
Total	12	391.359			

SOURCE	DF	SEQ SS
QC1	1	375.065
FR	1	6.995
PP	1	0.011
PO	1	2.204
QC1xFR	1	0.007
QC1xPP	1	2.175
QC1xPO	1	0.413
FRxPP	1	1.884
PPxPO	1	0.402

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
1	158	3.226	3.231	0.857	-0.005	-1.69 X
7	247	5.074	5.087	0.857	-0.013	-1.11 X

X denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.964

MTB > WRITE 'TR2A.OUT' C12 C99

MTB > READ 'TR2B.DAT' C1-C5
63 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	6.67	104.34	1.00	0.12	1.82
2	11.70	126.25	0.72	0.27	1.87
3	15.24	120.76	0.73	0.10	1.90
4	10.71	103.33	0.88	-0.42	1.96

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * FR is highly correlated with other predictor variables

NOTE * PP is highly correlated with other predictor variables

NOTE * FRxPO is highly correlated with other predictor variables

NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

$$C1/N1 = 0.0496 QC1 - 3.69 FR - 2.27 PP + 4.06 PO + 0.0215 QC1xFR \\ + 0.0351 QC1xPP - 0.0357 QC1xPO + 1.04 FRxPP + 1.09 FRxPO \\ - 0.397 PPxPO$$

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.04955	0.01284	3.86	0.000
FR	-3.693	1.918	-1.93	0.060
PP	-2.270	2.926	-0.78	0.441
PO	4.061	1.031	3.94	0.000
QC1xFR	0.021475	0.007148	3.00	0.004
QC1xPP	0.03508	0.01143	3.07	0.003
QC1xPO	-0.03565	0.01066	-3.34	0.002
FRxPP	1.0414	0.7062	1.47	0.146
FRxPO	1.090	1.162	0.94	0.352
PPxPO	-0.3974	0.7705	-0.52	0.608

s = 2.155

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	2358.26	235.83	50.80	0.000
Error	53	246.02	4.64		
Total	63	2604.28			

SOURCE	DF	SEQ SS
QC1	1	2182.18
FR	1	46.43
PP	1	4.94
PO	1	18.19
QC1xFR	1	24.31
QC1xPP	1	21.52
QC1xPO	1	34.88
FRxPP	1	20.85
FRxPO	1	3.72
PPxPO	1	1.23

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
1	104	15.643	6.527	0.379	9.117	4.30R
37	40	2.280	2.279	2.106	0.002	0.00 X
47	82	11.268	5.705	0.487	5.564	2.65R
53	24	3.707	3.800	2.006	-0.094	-0.12 X
54	242	4.993	8.881	0.951	-3.888	-2.01R
56	351	14.403	12.530	1.588	1.873	1.29 X
57	262	13.914	15.012	1.975	-1.099	-1.27 X
61	24	2.335	2.365	1.820	-0.030	-0.03 X

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.691

MTB > WRITE 'TR2B.OUT' C12 C99

MTB > READ 'TR34.DAT' C1-C5

137 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	10.04	26.67	2.62	9.94	2.54
2	10.60	34.28	2.84	5.95	2.57
3	6.80	16.01	3.51	11.26	2.62
4	7.99	16.23	3.25	13.29	2.65

```

MTB > EXEC 'NAMES.PRG'
MTB > NAME C1 'N1'
MTB > NAME C2 'QC1'
MTB > NAME C3 'FR'
MTB > NAME C4 'PP'
MTB > NAME C5 'PO'
MTB > LET C6 = C2*C3
MTB > LET C7 = C2*C4
MTB > LET C8 = C2*C5
MTB > LET C9 = C3*C4
MTB > LET C10 = C3*C5
MTB > LET C11 = C4*C5
MTB > LET C12 = C2/C1
MTB > NAME C6 'QC1xFR'
MTB > NAME C7 'QC1xPP'
MTB > NAME C8 'QC1xPO'
MTB > NAME C9 'FRxPP'
MTB > NAME C10 'FRxPO'
MTB > NAME C11 'PPxPO'
MTB > NAME C12 'QC1/N1'
MTB > NOCONSTANT
MTB > REGRESS C12 ON 10 C2-C11 C98 C99
* NOTE *      FR is highly correlated with other predictor variables
* NOTE *      PP is highly correlated with other predictor variables
* NOTE *      QC1xPO is highly correlated with other predictor variables
* NOTE *      PPxPO is highly correlated with other predictor variables

```

The regression equation is

$$\begin{aligned}
 \text{QC1/N1} = & -0.0410 \text{ QC1} + 0.380 \text{ FR} + 0.211 \text{ PP} + 2.33 \text{ PO} + 0.0108 \text{ QC1xFR} \\
 & -0.0297 \text{ QC1xPP} + 0.0423 \text{ QC1xPO} + 0.0714 \text{ FRxPP} - 0.398 \text{ FRxPO} \\
 & -0.060 \text{ PPxPO}
 \end{aligned}$$

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	-0.04099	0.04533	-0.90	0.368
FR	0.3796	0.5950	0.64	0.525
PP	0.2110	0.4509	0.47	0.641
PO	2.3289	0.4961	4.69	0.000
QC1xFR	0.01077	0.01439	0.75	0.456
QC1xPP	-0.029725	0.006858	-4.33	0.000
QC1xPO	0.04231	0.02301	1.84	0.068
FRxPP	0.07138	0.05186	1.38	0.171
FRxPO	-0.3980	0.2434	-1.64	0.104
PPxPO	-0.0605	0.1172	-0.52	0.607

R = 2.243

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	4226.02	422.60	84.04	0.000
Error	127	638.66	5.03		
Total	137	4864.68			

SOURCE	DF	SEQ SS
QC1	1	3828.96
FR	1	20.05
PP	1	17.72
PO	1	180.46
QC1xFR	1	36.32
QC1xPP	1	97.02
QC1xPO	1	2.07
FRxPP	1	22.61
FRxPO	1	19.46
PPxPO	1	1.34

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
16	69.8	3.902	8.879	1.263	-4.976	-2.69RX
33	57.2	5.636	3.264	1.218	2.372	1.26 X
43	32.7	5.258	0.947	0.863	4.311	2.08R
57	21.0	9.439	4.004	0.484	5.435	2.48R
60	43.6	12.089	6.949	0.298	5.140	2.31R
61	49.7	14.003	7.587	0.333	6.416	2.89R
63	51.0	14.655	8.045	0.343	6.610	2.98R
80	23.7	1.783	1.528	2.088	0.255	0.31 X
81	10.0	2.209	3.724	1.094	-1.515	-0.77 X
90	12.4	2.557	3.402	1.140	-0.845	-0.44 X
97	44.6	3.799	8.849	0.611	-5.050	-2.34R
122	58.7	15.000	9.590	0.546	5.410	2.49R
124	39.5	15.449	8.219	0.428	7.230	3.28R

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.716

MTB > WRITE 'TR34.OUT' C12 C99

MTB > READ 'DB13.DAT' C1-C5

128 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	23.26	80.37	0.55	2.23	3.26
2	33.08	105.37	0.50	1.34	3.29
3	29.00	85.98	0.46	1.26	3.34
4	11.44	47.53	1.06	2.54	3.37

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

TB > NAME C12. 'QC1/N1'

TB > NOCONSTANT

TB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * QC1 is highly correlated with other predictor variables
 NOTE * PP is highly correlated with other predictor variables
 NOTE * QC1xPO is highly correlated with other predictor variables
 NOTE * FRxPO is highly correlated with other predictor variables
 NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

C1/N1 = 0.225 QC1 + 7.77 FR - 7.73 PP + 7.36 PO - 0.0780 QC1xFR
 + 0.0573 QC1xPP - 0.106 QC1xPO + 1.82 FRxPP - 4.08 FRxPO
 + 0.685 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Constant				
C1	0.22459	0.08566	2.62	0.010
FR	7.766	9.826	0.79	0.431
PP	-7.734	4.338	-1.78	0.077
PO	7.360	1.972	3.73	0.000
C1xFR	-0.07795	0.09740	-0.80	0.425
C1xPP	0.05728	0.02999	1.91	0.059
C1xPO	-0.10617	0.03031	-3.50	0.001
FRxPP	1.825	1.297	1.41	0.162
FRxPO	-4.076	4.045	-1.01	0.316
PPxPO	0.6852	0.9858	0.70	0.488

R-squared = 8.003

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	11551.0	1155.1	18.03	0.000
Error	118	7558.5	64.1		
Total	128	19109.5			

SOURCE	DF	SEQ SS
C1	1	8945.2
FR	1	193.6
PP	1	309.1
PO	1	688.7
C1xFR	1	114.1
C1xPP	1	207.8
C1xPO	1	960.8
FRxPP	1	65.4
FRxPO	1	35.3
PPxPO	1	30.9

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
20	45	2.033	2.474	4.379	-0.441	-0.07 X
21	34	1.669	5.305	5.885	-3.636	-0.67 X
22	41	6.382	4.151	4.481	2.231	0.34 X
28	38	4.867	1.812	4.208	3.055	0.45 X
56	105	2.906	6.287	4.254	-3.382	-0.50 X
57	144	2.953	9.729	3.949	-6.776	-0.97 X
61	39	3.617	4.175	5.709	-0.558	-0.10 X
69	68	53.929	12.214	1.274	41.715	5.28R
71	90	49.022	10.430	1.153	38.591	4.87R

72	86	35.449	10.524	1.126	24.925	3.15R
73	108	29.975	9.475	1.370	20.500	2.60R
80	31	3.371	10.155	4.248	-6.784	-1.00 X
91	90	26.735	10.719	1.408	16.016	2.03R

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.377

MTB > NOTE REMOVE ALL OBSERVATIONS WITH QC1/N1 > 25

NOTE *** Data Editor entered at this point.

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * QC1 is highly correlated with other predictor variables
 NOTE * PP is highly correlated with other predictor variables
 NOTE * QC1xPO is highly correlated with other predictor variables
 NOTE * FRxPO is highly correlated with other predictor variables
 NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

$C1/N1 = 0.140 QC1 + 8.03 FR - 5.76 PP + 5.29 PO - 0.0233 QC1xFR$
 $+ 0.0269 QC1xPP - 0.0658 QC1xPO + 1.24 FRxPP - 4.17 FRxPO$
 $+ 0.795 PPxPO$

Predictor	Coef	Stdev	t-ratio	p
Constant				
C1	0.13976	0.04858	2.88	0.005
FR	8.029	5.532	1.45	0.150
PP	-5.761	2.478	-2.33	0.022
PO	5.289	1.130	4.68	0.000
C1xFR	-0.02332	0.05503	-0.42	0.673
C1xPP	0.02689	0.01697	1.58	0.116
C1xPO	-0.06576	0.01718	-3.83	0.000

FRxPP
FRxPO

1.2438
-4.172

0.7364
2.292

1.69
-1.82

0.094
0.071

PPxPO 0.7952 0.5587 1.42 0.157

s = 4.474

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	7215.63	721.56	36.05	0.000
Error	111	2221.99	20.02		
Total	121	9437.62			

SOURCE	DF	SEQ SS
QC1	1	5817.41
FR	1	165.36
PP	1	113.56
PO	1	431.90
QC1xFR	1	52.31
QC1xPP	1	167.92
QC1xPO	1	388.76
FRxPP	1	8.35
FRxPO	1	29.51
PPxPO	1	40.55

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
20	45	2.033	1.863	2.451	0.170	0.05 X
21	34	1.669	5.289	3.310	-3.619	-1.20 X
22	41	6.382	3.307	2.509	3.075	0.83 X
25	101	21.487	6.449	1.033	15.038	3.45R
28	38	4.867	3.883	2.367	0.984	0.26 X
56	105	2.906	5.792	2.382	-2.886	-0.76 X
57	144	2.953	7.184	2.230	-4.232	-1.09 X
61	39	3.617	3.526	3.192	0.090	0.03 X
62	93	19.584	8.371	1.015	11.213	2.57R
64	89	22.425	8.800	0.762	13.624	3.09R
67	41	21.497	8.804	1.547	12.693	3.02R
75	31	3.371	8.344	2.395	-4.973	-1.32 X
90	81	19.097	9.637	0.729	9.460	2.14R
99	68	21.732	8.242	0.828	13.491	3.07R
120	105	18.243	7.323	0.652	10.921	2.47R

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.443

MTB > NOTE: RESTART AGAIN

MTB > READ 'DB13.DAT' C1-C5

128 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	23.26	80.37	0.55	2.23	3.26
2	33.08	105.37	0.50	1.34	3.29
3	29.00	85.98	0.46	1.26	3.34
4	11.44	47.53	1.06	2.54	3.37

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

* NOTE * QC1 is highly correlated with other predictor variables
 * NOTE * PP is highly correlated with other predictor variables
 * NOTE * QC1xPO is highly correlated with other predictor variables
 * NOTE * FRxPO is highly correlated with other predictor variables
 * NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

$$\text{QC1/N1} = 0.225 \text{ QC1} + 7.77 \text{ FR} - 7.73 \text{ PP} + 7.36 \text{ PO} - 0.0780 \text{ QC1xFR} \\ + 0.0573 \text{ QC1xPP} - 0.106 \text{ QC1xPO} + 1.82 \text{ FRxPP} - 4.08 \text{ FRxPO} \\ + 0.685 \text{ PPxPO}$$

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.22459	0.08566	2.62	0.010
FR	7.766	9.826	0.79	0.431
PP	-7.734	4.338	-1.78	0.077
PO	7.360	1.972	3.73	0.000
QC1xFR	-0.07795	0.09740	-0.80	0.425
QC1xPP	0.05728	0.02999	1.91	0.059
QC1xPO	-0.10617	0.03031	-3.50	0.001
FRxPP	1.825	1.297	1.41	0.162
FRxPO	-4.076	4.045	-1.01	0.316
PPxPO	0.6852	0.9858	0.70	0.488

= 8.003

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	11551.0	1155.1	18.03	0.000
Error	118	7558.5	64.1		
Total	128	19109.5			

SOURCE	DF	SEQ SS
QC1	1	8945.2
FR	1	193.6
PP	1	309.1
PO	1	688.7
QC1xFR	1	114.1
QC1xPP	1	207.8
QC1xPO	1	960.8
FRxPP	1	65.4
FRxPO	1	35.3
PPxPO	1	30.9

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
20	45	2.033	2.474	4.379	-0.441	-0.07 X
21	34	1.669	5.305	5.885	-3.636	-0.67 X
22	41	6.382	4.151	4.481	2.231	0.34 X
28	38	4.867	1.812	4.208	3.055	0.45 X
56	105	2.906	6.287	4.254	-3.382	-0.50 X
57	144	2.953	9.729	3.949	-6.776	-0.97 X
61	39	3.617	4.175	5.709	-0.558	-0.10 X
69	68	53.929	12.214	1.274	41.715	5.28R
71	90	49.022	10.430	1.153	38.591	4.87R

MTB > PLOT C12 C3

MTB > PLOT C12 C4

MTB > PLOT C12 C5

MTB > LET C13 = LOGTEN(C1)

MTB > PLOT C12 C13

MTB > PLOT C12 C3

MTB > PLOT C12 C4

MTB > PLOT C12 C5

MTB > DOTPLOT C12

MTB > NOTE REMOVE ALL OBSERVATIONS WITH QC1/N1 > 16

NOTE *** Data Editor entered at this point.

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

* NOTE * QC1 is highly correlated with other predictor variables
 * NOTE * PP is highly correlated with other predictor variables
 * NOTE * QC1xPO is highly correlated with other predictor variables
 * NOTE * FRxPO is highly correlated with other predictor variables
 * NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

QC1/N1 = 0.116 QC1 + 6.13 FR - 5.62 PP + 5.06 PO - 0.0071 QC1xFR
 + 0.0232 QC1xPP - 0.0586 QC1xPO + 1.34 FRxPP - 3.90 FRxPO
 + 0.809 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.11568	0.03549	3.26	0.002
FR	6.132	3.916	1.57	0.120
PP	-5.625	1.736	-3.24	0.002
PO	5.0553	0.7980	6.34	0.000
QC1xFR	-0.00706	0.03916	-0.18	0.857
QC1xPP	0.02322	0.01199	1.94	0.055
QC1xPO	-0.05859	0.01235	-4.74	0.000
FRxPP	1.3389	0.5153	2.60	0.011
FRxPO	-3.903	1.599	-2.44	0.016
PPxPO	0.8090	0.3921	2.06	0.042

s = 3.104

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	5198.47	519.85	53.96	0.000
Error	103	992.26	9.63		
Total	113	6190.73			

SOURCE	DF	SEQ SS
QC1	1	4129.49
FR	1	125.97
PP	1	50.78
PO	1	384.03
QC1xFR	1	33.40
QC1xPP	1	139.08
QC1xPO	1	253.90
FRxPP	1	18.58
FRxPO	1	22.24
PPxPO	1	41.01

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
20	45	2.033	1.944	1.706	0.089	0.03 X
21	34	1.669	6.231	2.303	-4.561	-2.19RX
22	41	6.382	3.845	1.745	2.538	0.99 X
26	76	14.703	7.609	0.599	7.095	2.33R
27	38	4.867	3.671	1.652	1.196	0.46 X
38	130	11.657	4.367	1.319	7.291	2.59R
44	76	15.839	8.781	0.647	7.058	2.32R
54	105	2.906	4.984	1.678	-2.079	-0.80 X
59	39	3.617	3.058	2.220	0.559	0.26 X
61	63	15.926	7.976	0.488	7.951	2.59R
63	90	14.617	6.992	0.501	7.625	2.49R
68	66	14.086	7.254	0.529	6.832	2.23R
70	31	3.371	6.359	1.767	-2.988	-1.17 X
79	75	2.566	8.672	0.586	-6.106	-2.00R

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

TB > DOTPLOT C12

TB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.525

MTB > READ 'DB4.DAT' C1-C5
43 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	13.16	15.23	2.80	9.39	4.21
2	5.83	14.66	2.29	16.03	4.24
3	7.72	13.69	1.74	18.82	4.29
4	10.58	11.70	2.08	19.61	4.32

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * QC1 is highly correlated with other predictor variables

NOTE * FR is highly correlated with other predictor variables

NOTE * PP is highly correlated with other predictor variables

NOTE * PO is highly correlated with other predictor variables

NOTE * QC1xPO is highly correlated with other predictor variables

NOTE * FRxPP is highly correlated with other predictor variables

NOTE * FRxPO is highly correlated with other predictor variables

NOTE * PPxPO is highly correlated with other predictor variables

the regression equation is

C1/N1 = 0.045 QC1 - 8.76 FR - 0.35 PP + 6.23 PO + 0.229 QC1xFR - 0.0050 QC1xPP
- 0.0805 QC1xPO + 0.553 FRxPP - 0.93 FRxPO - 0.181 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.0446	0.2147	0.21	0.837
FR	-8.756	8.545	-1.02	0.313
PP	-0.349	1.305	-0.27	0.791
PO	6.226	2.071	3.01	0.005
QC1xFR	0.2293	0.1157	1.98	0.056
QC1xPP	-0.00499	0.01760	-0.28	0.779
QC1xPO	-0.08048	0.05283	-1.52	0.137
FRxPP	0.5528	0.2899	1.91	0.065
FRxPO	-0.930	2.420	-0.38	0.703
PPxPO	-0.1814	0.2606	-0.70	0.491

s = 3.519

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	967.99	96.80	7.82	0.000
Error	33	408.60	12.38		
Total	43	1376.59			

SOURCE	DF	SEQ SS
QC1	1	799.69
FR	1	3.70
PP	1	0.55
PO	1	50.90
QC1xFR	1	0.44
QC1xPP	1	1.77
QC1xPO	1	56.35
FRxPP	1	22.59
FRxPO	1	26.00
PPxPO	1	6.00

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
11	72.3	6.490	6.047	3.334	0.443	0.39 X
42	26.9	24.917	9.449	1.839	15.467	5.16R

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > NOTE REMOVE ALL OBSERVATIONS WITH QC1/N1 > 10

NOTE *** Data Editor entered at this point.

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * QC1 is highly correlated with other predictor variables
 NOTE * FR is highly correlated with other predictor variables
 NOTE * PP is highly correlated with other predictor variables
 NOTE * PO is highly correlated with other predictor variables
 NOTE * QC1xPO is highly correlated with other predictor variables
 NOTE * FRxPP is highly correlated with other predictor variables
 NOTE * FRxPO is highly correlated with other predictor variables
 NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

$$\begin{aligned} \text{QC1/N1} = & 0.0480 \text{ QC1} + 0.77 \text{ FR} - 0.545 \text{ PP} + 1.93 \text{ PO} + 0.0450 \text{ QC1xFR} \\ & + 0.00521 \text{ QC1xPP} - 0.0206 \text{ QC1xPO} + 0.137 \text{ FRxPP} - 0.899 \text{ FRxPO} \\ & + 0.0284 \text{ PPxPO} \end{aligned}$$

Predictor	Coef	Stdev	t-ratio	p
Constant				
C1	0.04800	0.08270	0.58	0.566
R	0.768	3.055	0.25	0.803
P	-0.5449	0.4680	-1.16	0.253
O	1.9331	0.8065	2.40	0.023
C1xFR	0.04503	0.04479	1.01	0.323
C1xPP	0.005214	0.007632	0.68	0.500
C1xPO	-0.02055	0.01953	-1.05	0.301
RxPP	0.1369	0.1052	1.30	0.203
RxPO	-0.8990	0.8469	-1.06	0.297
PxPO	0.02842	0.09112	0.31	0.757

= 1.217

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	422.844	42.284	28.56	0.000
Error	30	44.419	1.481		
Total	40	467.263			

SOURCE	DF	SEQ SS
QC1	1	401.610
FR	1	2.752
PP	1	1.063
PO	1	3.869
QC1xFR	1	0.151
QC1xPP	1	2.829
QC1xPO	1	7.759
FRxPP	1	0.302
FRxPO	1	2.365
PPxPO	1	0.144

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
11	72.3	6.490	5.902	1.154	0.588	1.52 X
29	53.3	9.029	5.200	0.616	3.829	3.65R
30	66.3	2.935	5.391	0.814	-2.456	-2.72R

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

TB > DOTPLOT C12

TB > DOTPLOT C99

TB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.806

MTB > READ 'DB5.DAT' C1-C5

38 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	11.25	16.92	1.16	18.55	4.55
2	12.62	16.68	1.30	19.84	4.58
3	11.62	16.71	1.52	20.03	4.63
4	9.73	15.73	1.77	16.00	4.66

MTB > EXEC 'NAMES.PRG

* ERROR * Missing or stray quote

* Name or file may be ignored

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

* NOTE * QC1 is highly correlated with other predictor variables

* NOTE * FR is highly correlated with other predictor variables

* NOTE * PP is highly correlated with other predictor variables

* NOTE * PO is highly correlated with other predictor variables

* NOTE * QC1xFR is highly correlated with other predictor variables

* NOTE * QC1xPP is highly correlated with other predictor variables

* NOTE * QC1xPO is highly correlated with other predictor variables

* NOTE * FRxPO is highly correlated with other predictor variables

* NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

C1/N1 = 0.501 QC1 - 7.37 FR + 0.272 PP - 0.140 PO - 0.0670 QC1xFR
 - 0.00175 QC1xPP - 0.0772 QC1xPO - 0.0006 FRxPP + 2.27 FRxPO
 - 0.0824 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	0.5010	0.1604	3.12	0.004
FR	-7.375	2.453	-3.01	0.006
PP	0.2722	0.2361	1.15	0.259
PO	-0.1399	0.7770	-0.18	0.858
QC1xFR	-0.06697	0.06076	-1.10	0.280
QC1xPP	-0.001752	0.001889	-0.93	0.362
QC1xPO	-0.07719	0.03331	-2.32	0.028
FRxPP	-0.00060	0.04420	-0.01	0.989
FRxPO	2.2721	0.7150	3.18	0.004
PPxPO	-0.08243	0.05978	-1.38	0.179

s = 0.9100

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	214.208	21.421	25.87	0.000
Error	28	23.186	0.828		
Total	38	237.394			

SOURCE	DF	SEQ SS
QC1	1	172.501
FR	1	10.176
PP	1	5.953
PO	1	12.180
QC1xFR	1	0.218
QC1xPP	1	1.557
QC1xPO	1	1.202
FRxPP	1	1.507
FRxPO	1	7.340
PPxPO	1	1.575

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
5	17.3	5.376	2.885	0.287	2.491	2.88R
16	28.7	4.281	4.217	0.809	0.064	0.15 X
23	46.0	0.872	0.822	0.824	0.050	0.13 X
37	15.4	4.242	2.458	0.381	1.784	2.16R
38	20.1	1.949	2.604	0.863	-0.655	-2.27RX

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

MTB > DOTPLOT C99

MTB > CORR C12 C99

Correlation of QC1/N1 and C99 = 0.781

MTB > READ 'ST.DAT' C1-C5
176 ROWS READ

ROW	N1	QC1	FR	PP	PO
1	4.63	83.23	1.11	1.18	4.67
2	2.30	49.03	1.55	2.23	4.73
3	13.31	53.37	1.28	2.09	4.75
4	14.59	80.03	0.51	0.66	4.81

MTB > EXEC 'NAMES.PRG'

MTB > NAME C1 'N1'

MTB > NAME C2 'QC1'

MTB > NAME C3 'FR'

MTB > NAME C4 'PP'

MTB > NAME C5 'PO'

MTB > LET C6 = C2*C3

MTB > LET C7 = C2*C4

MTB > LET C8 = C2*C5

MTB > LET C9 = C3*C4

MTB > LET C10 = C3*C5

MTB > LET C11 = C4*C5

MTB > LET C12 = C2/C1

MTB > NAME C6 'QC1xFR'

MTB > NAME C7 'QC1xPP'

MTB > NAME C8 'QC1xPO'

MTB > NAME C9 'FRxPP'

MTB > NAME C10 'FRxPO'

MTB > NAME C11 'PPxPO'

MTB > NAME C12 'QC1/N1'

MTB > NOCONSTANT

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

* NOTE * QC1 is highly correlated with other predictor variables
 * NOTE * FR is highly correlated with other predictor variables
 * NOTE * PP is highly correlated with other predictor variables
 * NOTE * QC1xPP is highly correlated with other predictor variables
 * NOTE * QC1xPO is highly correlated with other predictor variables
 * NOTE * FRxPO is highly correlated with other predictor variables
 * NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

QC1/N1 = - 0.079 QC1 + 4.47 FR - 0.82 PP + 1.33 PO + 0.0223 QC1xFR
 + 0.000642 QC1xPP + 0.0238 QC1xPO + 0.119 FRxPP - 1.34 FRxPO
 + 0.075 PPxPO

Predictor	Coef	Stdev	t-ratio	p
Noconstant				
QC1	-0.0787	0.1394	-0.56	0.573
FR	4.471	9.197	0.49	0.627
PP	-0.820	2.125	-0.39	0.700
PO	1.3331	0.6170	2.16	0.032
QC1xFR	0.02232	0.03382	0.66	0.510
QC1xPP	0.0006421	0.0004358	1.47	0.143
QC1xPO	0.02378	0.03082	0.77	0.441
FRxPP	0.1186	0.1793	0.66	0.509
FRxPO	-1.341	1.909	-0.70	0.484
PPxPO	0.0751	0.4111	0.18	0.855

s = 10.27

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	17040.1	1704.0	16.15	0.000
Error	166	17512.9	105.5		
Total	176	34553.0			

SOURCE	DF	SEQ SS
QC1	1	16218.5
FR	1	25.4
PP	1	2.0
PO	1	211.1
QC1xFR	1	6.2
QC1xPP	1	459.8
QC1xPO	1	23.7
FRxPP	1	33.3
FRxPO	1	56.5
PPxPO	1	3.5

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
40	105	7.820	12.642	4.288	-4.822	-0.52 X
68	54	1.425	5.997	5.225	-4.572	-0.52 X
87	63	41.500	5.545	1.566	35.955	3.54R
94	1178	105.112	105.102	10.271	0.010	0.19 X
96	-362	20.652	18.317	7.947	2.336	0.36 X
103	39	1.470	1.285	4.668	0.185	0.02 X
127	25	1.226	-2.502	6.970	3.728	0.49 X
146	78	56.304	8.715	1.390	47.590	4.68R
147	54	117.261	7.233	1.206	110.028	10.79R
167	16	1.340	-1.178	5.578	2.518	0.29 X

denotes an obs. with a large st. resid.

denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12

each dot represents 5 points

MTB > DOTPLOT C99

Each dot represents 3 points

MTB > NOTE REMOVE ALL QC1/N1 > 25

NOTE *** Data Editor entered at this point.

MTB > REGRESS C12 ON 10 C2-C11 C98 C99

NOTE * QC1 is highly correlated with other predictor variables
 NOTE * FR is highly correlated with other predictor variables
 NOTE * PP is highly correlated with other predictor variables
 NOTE * QC1xPO is highly correlated with other predictor variables
 NOTE * FRxPO is highly correlated with other predictor variables
 NOTE * PPxPO is highly correlated with other predictor variables

The regression equation is

$$\begin{aligned} \text{C1/N1} = & -0.0651 \text{ QC1} + 3.34 \text{ FR} - 0.215 \text{ PP} + 0.697 \text{ PO} + 0.0195 \text{ QC1xFR} \\ & + 0.00220 \text{ QC1xPP} + 0.0196 \text{ QC1xPO} + 0.0062 \text{ FRxPP} - 0.918 \text{ FRxPO} \\ & + 0.017 \text{ PPxPO} \end{aligned}$$

Predictor	Coef	Stdev	t-ratio	p
Constant				
C1	-0.06505	0.04180	-1.56	0.122
FR	3.342	2.620	1.28	0.204
PP	-0.2149	0.6335	-0.34	0.735
PO	0.6975	0.2348	2.97	0.003
C1xFR	0.019452	0.009887	1.97	0.051
C1xPP	0.002203	0.001859	1.18	0.238
C1xPO	0.01959	0.01028	1.91	0.058
FRxPP	0.00623	0.05197	0.12	0.905
FRxPO	-0.9183	0.5459	-1.68	0.094
PPxPO	0.0174	0.1192	0.15	0.884

= 2.919

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	10	3486.01	348.60	40.90	0.000
Error	161	1372.10	8.52		
Total	171	4858.11			

SOURCE	DF	SEQ SS
QC1	1	3186.08
FR	1	38.02
PP	1	1.20
PO	1	146.69
QC1xFR	1	24.43
QC1xPP	1	43.65
QC1xPO	1	12.52
FRxPP	1	0.23
FRxPO	1	33.01
PPxPO	1	0.18

Unusual Observations

Obs.	QC1	QC1/N1	Fit	Stdev.Fit	Residual	St.Resid
1	83	17.976	6.272	0.455	11.704	4.06R
2	49	21.317	4.546	0.345	16.771	5.79R
18	90	14.030	7.849	0.736	6.180	2.19R
21	33	14.705	3.935	0.418	10.770	3.73R
22	43	13.850	4.608	0.416	9.242	3.20R
40	105	7.820	9.295	1.358	-1.475	-0.57 X
68	54	1.425	4.816	1.586	-3.391	-1.38 X
75	153	2.973	8.606	1.083	-5.633	-2.08R
79	139	17.029	9.315	1.143	7.714	2.87R
93	362	20.652	20.243	2.722	0.409	0.39 X
100	39	1.470	1.869	1.345	-0.398	-0.15 X
112	21	8.824	2.379	0.439	6.445	2.23R
124	25	1.226	0.745	1.990	0.481	0.23 X
162	16	1.340	-0.421	1.616	1.761	0.72 X

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.

MTB > DOTPLOT C12