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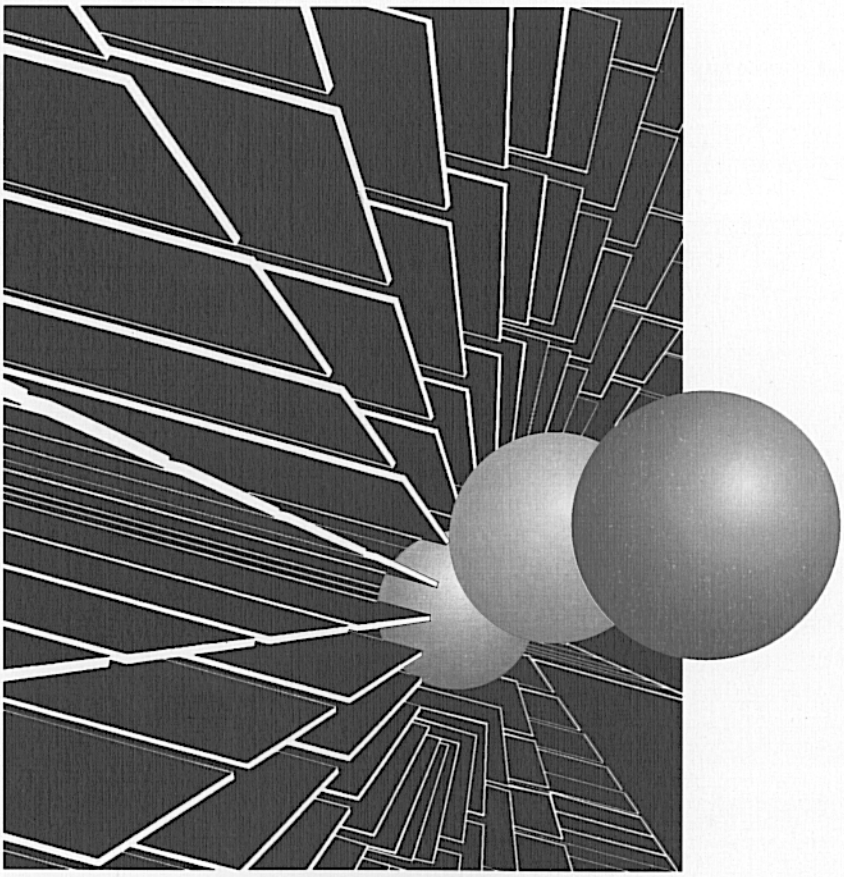
RDT 00-003

3-D Computer Modeling of Subsurface Conditions for Bridge Foundations

RI 99-027



May, 2000

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. RDT 00-003	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 3-D Computer Modeling of Subsurface Conditions for Bridge Foundations		5. Report Date May 2000
		6. Performing Organization Code University of Missouri - Columbia
7. Author(s) J. Erik Loehr		8. Performing Organization Report No. RDT 00-003 / RI99-027
9. Performing Organization Name and Address University of Missouri - Columbia; Dept. Of Civil and Environmental Engineering E2509 Engineering Building East Columbia, MO 65211-2200		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Missouri Department of Transportation Research, Development and Technology Division; P. O. Box 270 Jefferson City, MO 65102		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code MoDOT

15. Supplementary Notes

The investigation was conducted by the University of Missouri - Columbia in cooperation with the Missouri Department of Transportation.

16. Abstract

A study was conducted to evaluate the potential for using three-dimensional computer modeling to assist MoDOT Soils and Geology personnel and Bridge Division personnel in developing accurate and realistic understanding of subsurface conditions for bridge structures. Secondary objectives of the study included developing a preliminary procedure for development of three-dimensional geologic models of bridge sites and identifying key issues to be addressed for more widespread use of three-dimensional modeling activities.

The site of a proposed new bridge across the Missouri River near Lexington, Missouri was selected as a demonstration case study for three-dimensional geologic modeling. Several separate models of this site were developed during the project to demonstrate the different levels of abstraction for a 3-D model of a particular site. The computer models developed are presented and described in this report.

The models developed for this project illustrate the types of 3-D computer models that can be generated using currently available software. It is recommended that an expanded pilot program be implemented to include modeling of several additional sites. The expanded pilot program should include modeling of geologic conditions during site investigation and should be performed by personnel that are intimately involved with site investigation activities. In addition, interim versions of 3-D models developed during site investigation should be used to assist in selecting locations for additional borings.

17. Key Words Site investigation, bridge foundations, 3-D computer modeling, geologic modeling		18. Distribution Statement No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 30	22. Price

Form DOT F 1700.7 (06/98)

3-D Computer Modeling of Subsurface Conditions for Bridge Foundations

Final Report

Project No. RDT RI99-2700

Prepared for

Missouri Department of Transportation
Bridge and Research Development and Technology Divisions

by

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April 25, 2000

The opinions, findings, and conclusions expressed in this publication are those of the principal investigators and the Research, Development and Technology Division of the Missouri Department of Transportation. They are not necessarily those of the U.S. Department of Transportation, Federal Highway Administration. This report does not constitute a standard or regulation.

Table of Contents

Table of Contents i
List of Figures ii
List of Tables iii
1. Introduction 1
2. Geologic Modeling Software Tools 2
3. 3-D Solid Modeling Technique 2
3.1 GMS Modeling Tools 3
4. Lexington Site Computer Models 9
4.1 Lexington Site 9
4.2 Characteristics of Geologic Data 9
4.3 Modeling Process 10
4.4 Selection of Important Geologic Strata 10
4.5 Computer Models 10
4.5.1 Soil-Rock Model for Entire Site 11
4.5.2 Refined Model for River Pier Area 14
4.5.3 Refined Model of Entire Site 18
4.5.4 Comparison of Models 24
5. Key Issues for 3-D Computer Modeling of Subsurface Conditions 25
5.1 Sources of Uncertainty 25
5.2 Reporting and Visualization of Geologic Models 27
5.3 Contracting and Data Transfer Issues 27
6. Uses and Limitations of 3-D Computer Modeling 27
7. Summary of Geologic Modeling Software Packages 28
8. Potential Applications of 3-D Modeling – A Vision of the Future 29
9. Recommendations for Implementation of 3-D Modeling 29
10. References 30

List of Figures

Figure 3.1 Dialog box used for entering borehole contact coordinates and material identifiers. .. 3
Figure 3.2. Display of borings after input using Borehole Editor dialog box..... 4
Figure 3.3. Sample TIN representing the "profile surface" (contact) between geologic materials. 5
Figure 3.4. Group of TINs representing profile surfaces for all contacts at a site. 6
Figure 3.5. Extrusion of a TIN (a) to form a solid (b). (taken from Engineering Computer Graphics Laboratory, 1998)..... 7
Figure 3.6. Example set operations used to form a solid model representing geologic strata. (taken from Engineering Computer Graphics Laboratory, 1998)..... 8
Figure 3.7. Materials Editor dialog box used to define display attributes of each material. 8
Figure 4.1. Horizontal view of solid model for simple soil-rock model of Lexington Bridge Site. Vertical exaggeration = 10. 11
Figure 4.2. Inclined view of simple soil-rock solid model for Lexington Bridge site. Vertical exaggeration = 10..... 12
Figure 4.3. Inclined view of cross-sections through solid model for simple soil-rock model of Lexington Bridge site. Vertical exaggeration = 10..... 13
Figure 4.4. Inclined view of solid model for refined model of river crossing area..... 14
Figure 4.5. Inclined view of solid model for refined model of river crossing area with overburden material solids removed. 15
Figure 4.6. Inclined view of cross-sections through refined solid model of river crossing area. .. 15
Figure 4.7. Horizontal view of cross-sections through refined model of river crossing area..... 16
Figure 4.8. Inclined view of river crossing area with isolated solid model of Pier 21. 16
Figure 4.9. Close up inclined view of solid section for Pier 21. 17
Figure 4.10. Perspective view of borings for Lexington Bridge Site model. Vertical exaggeration = 10..... 19
Figure 4.11. Horizontal (x-z) view of borings for Lexington Bridge Site model. Vertical exaggeration = 5..... 20
Figure 4.12. Inclined view of solid model for refined model of entire site. Vertical exaggeration = 5.20
Figure 4.13. Isolated view of solids representing rock materials in refined model of entire site. Vertical exaggeration = 5..... 21
Figure 4.14. Horizontal view of solid model for refined model of entire site. Vertical exaggeration = 5..... 21
Figure 4.15. Inclined view of cross-sections through refined solid model of entire site. Vertical exaggeration = 5..... 22
Figure 4.16. Inclined view of cross-sections through refined model of entire site. Vertical exaggeration = 5..... 23
Figure 4.17. Horizontal view of cross-sections through refined model of entire site. Vertical exaggeration = 5..... 24

List of Tables

Table 4.1. Summary of basis and criteria for establishing material categories for simple soil-rock model of entire site. 11
Table 4.2. Summary of basis and criteria for establishing material categories for refined solid model of river crossing area. 18
Table 4.3. Summary of basis and criteria for establishing material categories for refined model of entire site. 18
Table 7.1. Summary of capabilities of available geologic modeling software. 28

1. Introduction

Successful design of bridge foundations requires fundamental and thorough understanding of the subsurface conditions at a bridge site. Understanding of the geometry and properties of subsurface materials is thus a critical first step in developing cost effective and safe foundation designs for bridges and other structures. Interpretation of subsurface conditions generally begins with geotechnical or geological personnel developing a "picture" of the site (mental or otherwise) based on available geologic information obtained from boring logs and other geological and geotechnical data. In the large majority of cases, this interpretation is a reasonable representation of site conditions considering the limitations inherent to geotechnical investigations. However, there is often difficulty in conveying these subsurface conditions to other personnel due to the complexity of subsurface conditions present in even the simplest sites. Lack of a complete "picture" of subsurface conditions by all parties involved can lead to problems in both design and construction.

Development of three-dimensional computer models of subsurface conditions for bridge sites can be an extremely effective means for describing key elements of subsurface profiles and conveying a visual picture of the subsurface, which leads to an improved understanding of subsurface conditions by all parties. This more complete understanding of subsurface conditions will often lead to identification of potential problem conditions before construction begins and may lead to identification of beneficial alternative designs.

Three-dimensional modeling software also provides a number of direct benefits to geo-professionals developing an interpretation of the subsurface. The process of developing a visual computer model can lead to an improved understanding of the subsurface by facilitating management and display of large amounts of subsurface data that might otherwise be underutilized. Currently available software can dramatically speed up the process of plotting boring log information that would otherwise have to be plotted manually and permits rapid viewing of boring logs or 3-D models from an essentially infinite number of perspectives. By facilitating display of geotechnical information, the software assists with interpretation by:

- Highlighting locations where uncertainty about subsurface conditions is high;
- Providing direct feedback on potentially conflicting boring logs; and
- Identifying locations where additional subsurface investigation may be warranted.

Thus, while three-dimensional models of subsurface conditions will be no better than the data on which they are based and the skill of the interpreter, the process of developing models can enhance understanding of subsurface conditions for all involved.

A study was conducted during the period of September 1999 to January 2000 to evaluate the potential for using three-dimensional computer models to assist MoDOT Soils and Geology personnel and Bridge Division personnel in developing accurate and realistic understanding of subsurface conditions for bridge structures. Secondary objectives of the study were to develop a preliminary procedure for development of three-dimensional geologic models and to identify key issues that need to be addressed for further development and implementation of three-dimensional modeling activities on a routine basis.

The basic approach taken to meet the project objectives was to develop a three-dimensional computer model of the subsurface conditions for the proposed Bridge No. A-5664 over the Missouri River on Route 13 in Ray and Lafayette Counties (the "Lexington Bridge") as a "test case" for more general three-dimensional modeling. The Lexington site was deemed to a reasonable initial test for demonstrating the potential benefits of three-dimensional modeling of subsurface conditions for bridge sites. While geologic conditions at the site are relatively straight forward, the site investigation activities for the project are indicative of those undertaken for more complex sites. The site thus serves as a reasonable test of the ability to digitally store and display large amounts of data while limiting the difficulty with complex geological conditions. The process of developing the model for this site was also expected to lead to development of recommended procedures for developing similar models for other sites and to

identify key issues that need to be addressed further. The model was developed entirely using data obtained from site investigations previously performed and provided at project initiation.

This report describes the activities undertaken in this study and presents the results and recommendations arising from the work. A summary of the software used for developing the three-dimensional geologic models for this study is presented along with a brief description of the Lexington site. Three alternative models for the site are then described including the rationale for selecting important geologic features. Finally, several key issues that arose during modeling are discussed and a series of recommendations for further implementation of three-dimensional modeling activities are made.

2. Geologic Modeling Software Tools

The software used for development of three-dimensional computer models of the Lexington Bridge site is the Groundwater Modeling System (GMS) software developed at the Engineering Computer Graphics Laboratory at Brigham Young University. This software is commercially available from Environmental Modeling Systems, Inc. and a number of other engineering software clearinghouses. While GMS was specifically developed for modeling environmentally contaminated sites, it has an extensive suite of tools available for generating three-dimensional models of geologic sites that are equally well suited for traditional geotechnical modeling applications. The software is "modular" in that individual modules can be purchased to suit the needs of a particular organization thereby limiting expenditures to meet only required needs. The basic tools available in GMS that were used for developing the Lexington Bridge models are described below. This description is not meant to be a comprehensive description of all tools and techniques available or necessary for geologic modeling but rather a brief summary of tools and techniques to provide background necessary for understanding of the general modeling process.

3. 3-D Solid Modeling Technique

Software for three-dimensional geologic modeling generally falls into one of two categories. The first, and most common category of software are referred to as 4-D modeling software since they plot data consisting of a three-dimensional coordinate (3 dimensions) along with an additional scalar value (the 4th dimension). These programs are not necessarily specific to modeling geologic formations since they are essentially three-dimensional contouring programs designed to interpolate among data in three-dimensional space. While these programs are not always specific to geotechnical or geological modeling, they can be used for this purpose if a scalar data value can be associated with coordinates in three-dimensional space (e.g. water content, shear strength, permeability, etc). The second class of software is specific to geotechnical/geological modeling. These programs facilitate definition and description of layer interfaces, called "profile surfaces", and subsequently defining solids that describe geologic strata. This approach differs from 4-D software in that the resulting model is "truer" to the data rather than an interpolation of data. GMS has capabilities for creating both 4-D and layer interface types of models. The layer interface method was used for this project to provide contrast with 4-D models developed previously for the Cape Girardeau bridge site.

The basic modeling technique used for geologic modeling with solid models is to define "profile surfaces" that separate dissimilar geologic materials. These contacts are developed from contacts between different materials in boring logs and represent the boundaries between geologic strata. Once the key profile surfaces are defined, solids are generated using boolean operations to represent the volumes occupied by each material to form a solid model representing all geologic strata in the modeled region of soil. The process is thus rather simple in moving from known geologic data, the borehole data obtained in boring logs, to the three-dimensional representation of the subsurface conditions at a site. The tools and techniques employed with GMS are described below.

3.1 GMS Modeling Tools

The modules used for development of three-dimensional computer models include the following:

- Borehole Module,
- TIN Module,
- Solids Module,
- Map Module

The Borehole, TINs, and Solids modules are fundamental to generation of three-dimensional geologic models. The Map module is used for general annotation, visualization, and documentation of model attributes. In addition to these modules, GMS contains an extensive series of tools for general visualization. Specific descriptions of these modules and the general visualization tools used in this study are described below.

Borehole module. Basic geologic data obtained from conventional boring and sampling activities and other site investigation techniques such as cone penetration testing or borehole geophysics techniques are entered using the Borehole module. The general method for entering geologic data is through the "Borehole Editor" dialog box shown in Figure 3.1. In this dialog box, x, y, and z coordinates of geologic contacts obtained from boring logs are entered to define the interface between different geologic materials. Each borehole contact is associated with a particular material ID that is input using the Materials Editor described below. The number of boreholes and the number of contacts in a borehole are limited only by available computer memory. Once borehole data have been entered, the boreholes are displayed on screen using different colors and patterns to distinguish between different materials as shown in Figure 3.2. Borehole data are easily modified and enhanced after initial data entry allowing for updating of borehole data as new information (e.g. additional borings, laboratory test results) becomes available. The borehole module also has capabilities for storing and plotting data sets associated with boreholes such as moisture content, shear strength, SPT or CPT values, etc. This feature was not used in the current study. However, it does provide a useful tool for display and interpretation of geologic sites and several automated tools are available to assist the interpreter in selecting contacts between different geologic strata.

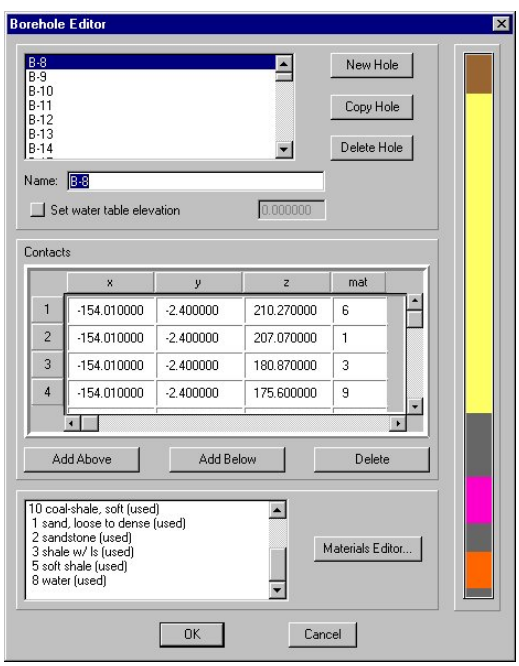


Figure 3.1 Dialog box used for entering borehole contact coordinates and material identifiers.

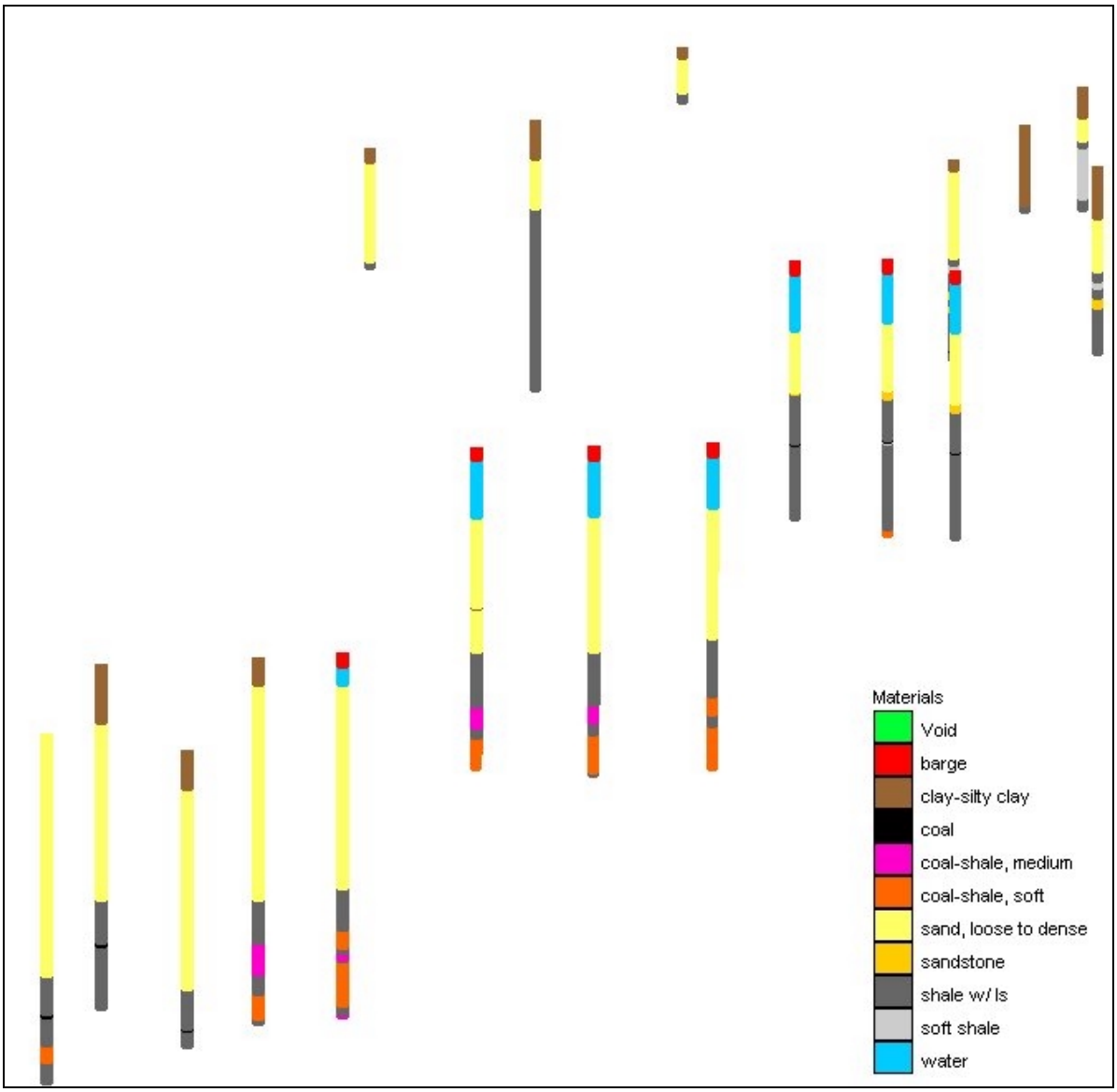
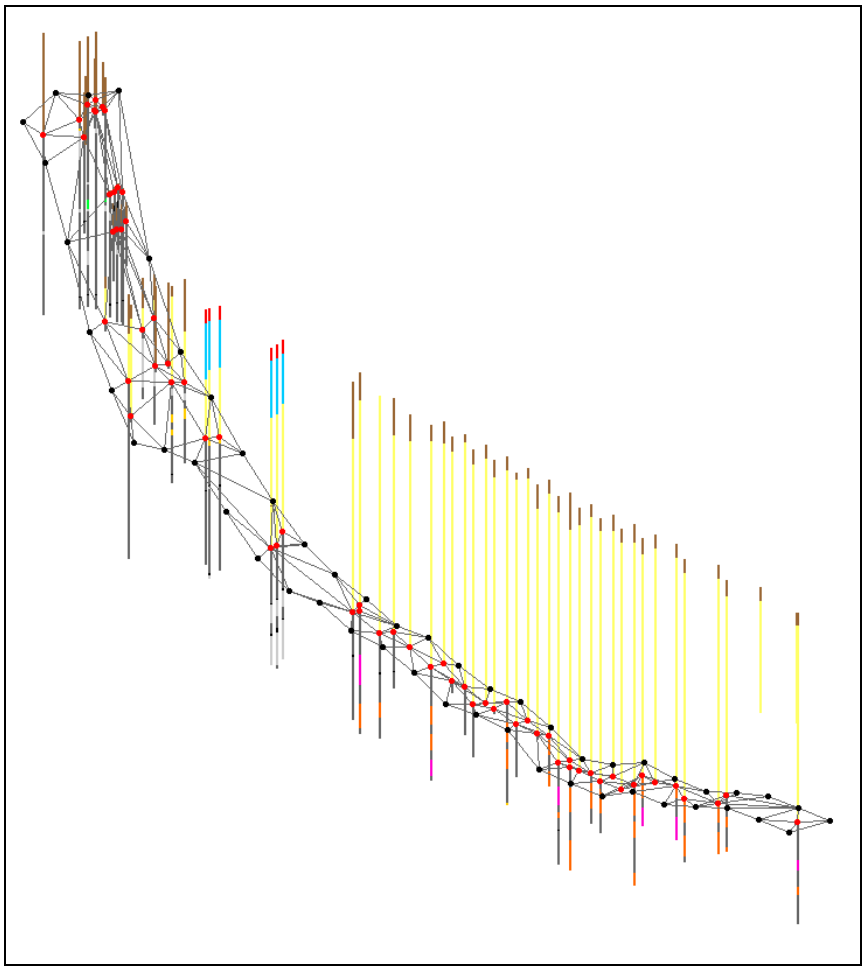
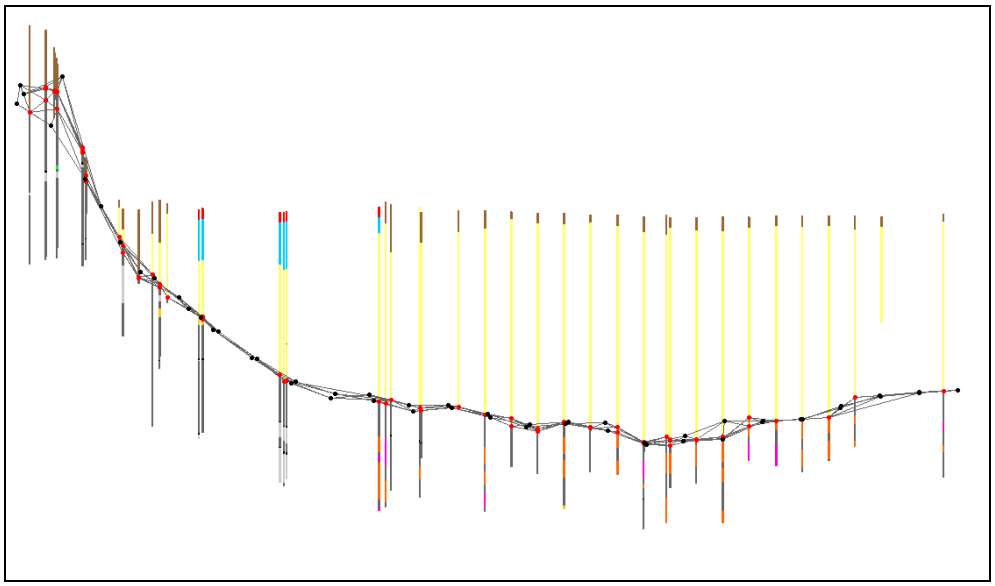


Figure 3.2. Display of borings after input using Borehole Editor dialog box.

TIN module. Three-dimensional profile surfaces describing the interface between geologic strata are represented in GMS using Triangulated Irregular Networks (TINs). TINs are formed of a series of nodes or vertices (x, y, z points) that represent key points on a surface. In the case of geologic modeling, the vertices are made to coincide with contacts of like geologic materials From these points, a surface is formed by creating a set of planar faces by triangulation using one of several algorithms. An example TIN is shown in Figure 3.3. The resulting surface thus consists of a group of piecewise planar faces representing the interface between geologic strata. While actual geologic surfaces are generally much smoother than that shown by a TIN, the TIN structure will be "true to the data" (the surface will match the location of contacts at all boreholes) thereby eliminating concern over whether or not an interpolation algorithm or other computer generated feature is producing information that is not consistent with observations. TINs can also be easily refined by inserting new vertices in a TIN so that updating and enhancing of the surface can be made according to the geologic interpretation or as new data (borehole data or otherwise) becomes available. Separate TINs are generated for each geologic interface in a model for preparation of solids as described next. A sample group of TINs defining the subsurface profile for the Lexington site is shown in Figure 3.4.

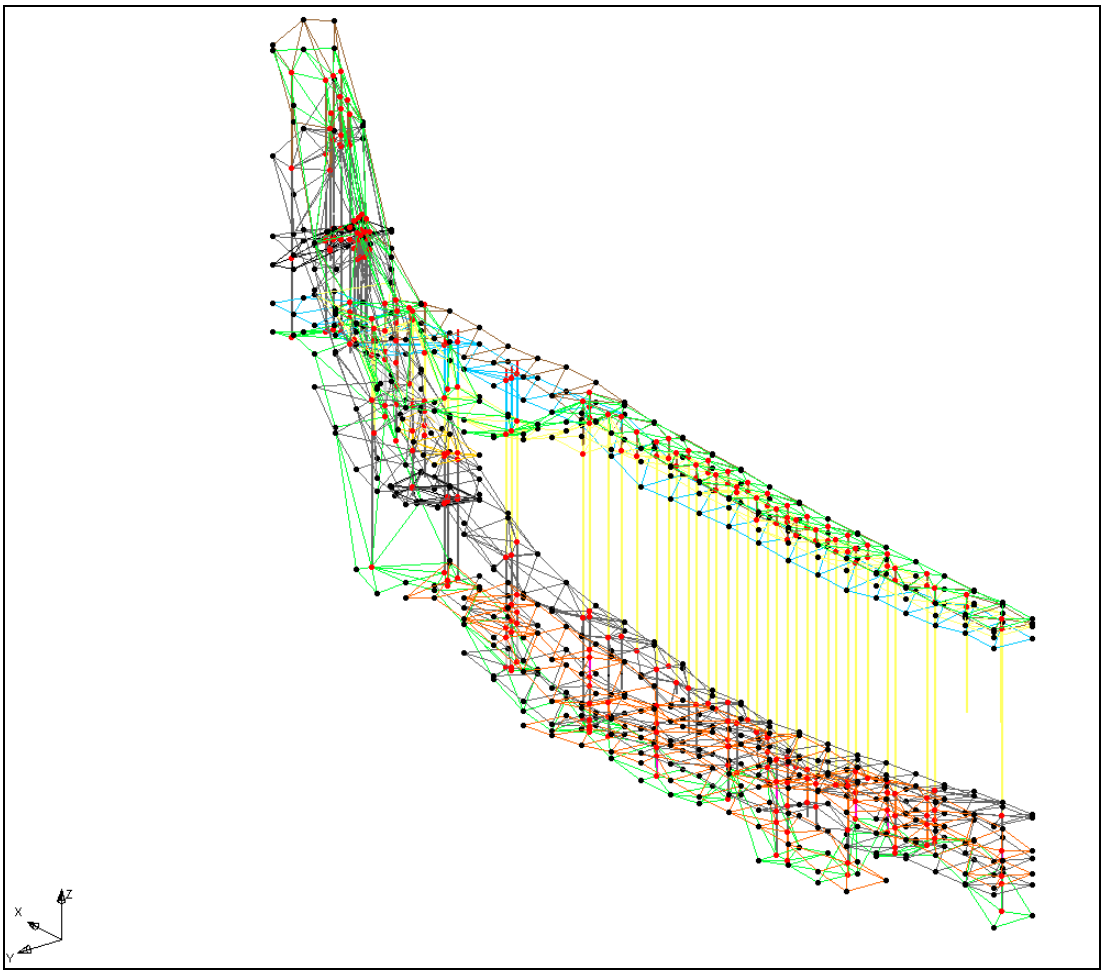


(a) inclined view

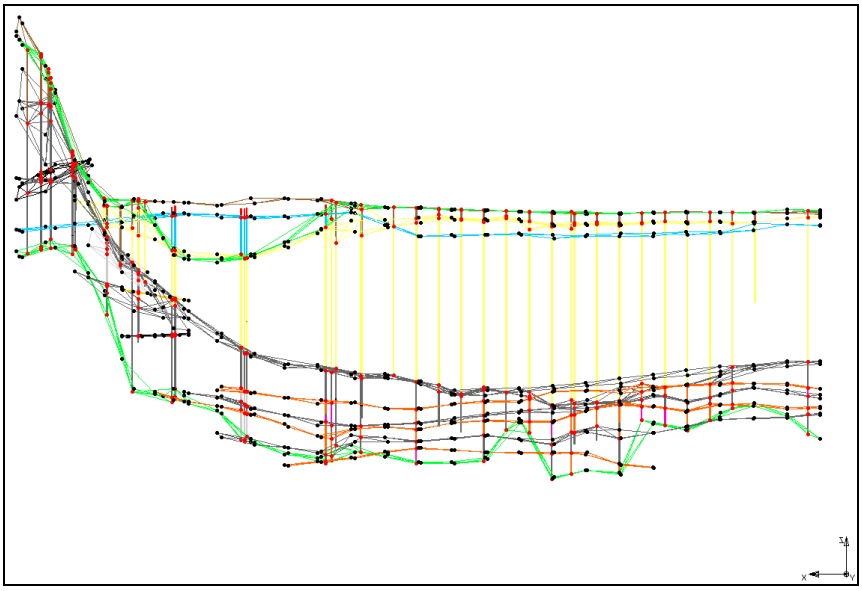


(b) horizontal view

Figure 3.3. Sample TIN representing the "profile surface" (contact) between geologic materials.



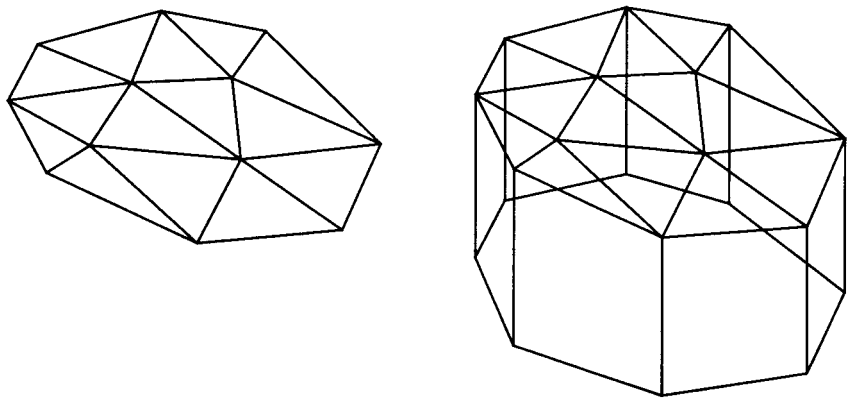
(a) inclined view



(b) horizontal view

Figure 3.4. Group of TINs representing profile surfaces for all contacts at a site.

Solids module. Once TINs are created for each geologic interface, the volume occupied by each stratum is modeled using solids. Solids are created by "extruding" a TIN over some distance to form a solid as shown in Figure 3.5. Alternatively, a solid can be created by "filling" between a pair of TINs that cover the same plan area. Once basic solids representing each material are created, boolean or set operations are used to refine the solids so that they fill only the volumes representing a particular stratum or material. The set operations available in GMS include "union", "intersection", and difference operations. A two-dimensional example of a series of set operations needed to form a set of solids for geologic modeling is shown in Figure 3.6. Once created, solids are generally not editable other than with set operations (e.g. it is not possible to simply move a "point" within a solid and have the solid reformed). As a result, it is generally necessary to create a series of temporary solids during the solid modeling process (e.g. solids P, Q, R, P-Q in Figure 3.6). These temporary solids can be eliminated once modeling is complete leaving only the final solids to form the solid model (solids P', Q', and R in Figure 3.6).



(a) (b)

Figure 3.5. Extrusion of a TIN (a) to form a solid (b). (taken from Engineering Computer Graphics Laboratory, 1998)

Materials Editor. Materials in GMS are represented with a simple material identification number that serves as a link between a material and the display attributes associated with a material. Materials are defined in GMS using the Material Editor dialog box shown in Figure 3.7. The attributes that can be set include the display color, the display pattern, and the material name. A material legend is also available that can be selectively displayed during all stages of modeling.

Other tools. In addition to the basic set of tools for geologic modeling, GMS has a series of general tools for visualization and display. Models can be interactively rotated for viewing from an infinite number of perspectives at any stage in model development (borehole, TINs, or solids). In addition, tools are available to plot contours of profile surfaces and to include plot axes using a variety of options. Cross-sections through a solid model can also be created and displayed and solids and TINs can be displayed as either wireframe or shaded images using several software options. A separate "Map" module can also be used to add annotation to a model or to import CAD and other digital drawings for display within GMS.

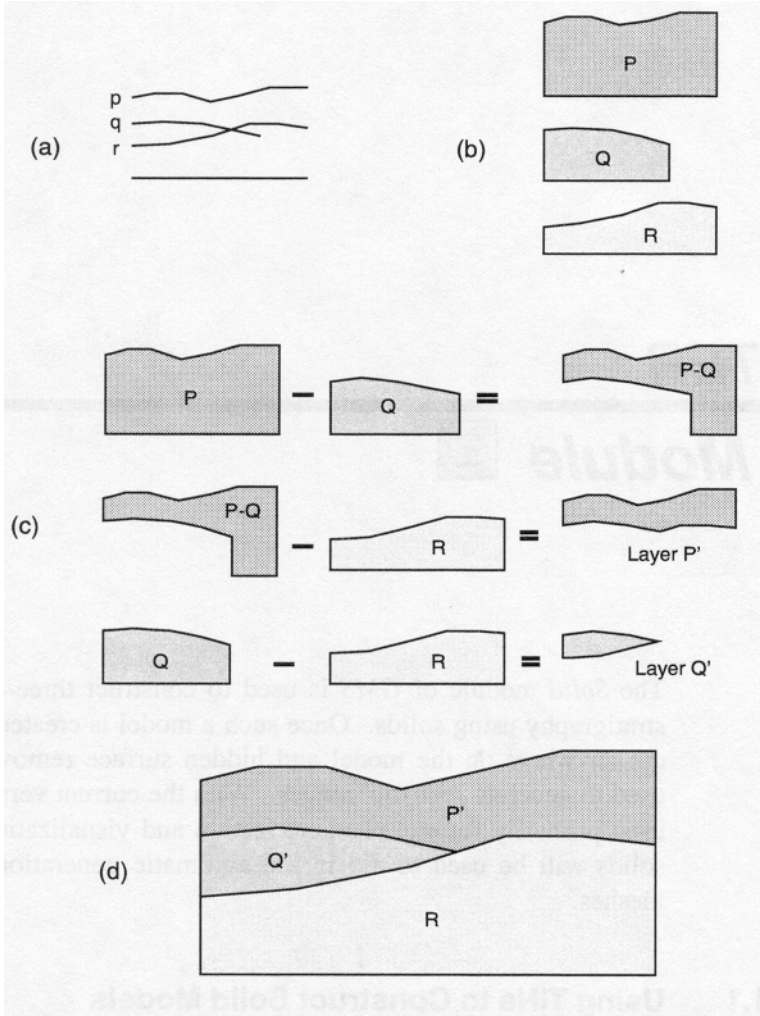


Figure 3.6. Example set operations used to form a solid model representing geologic strata. (taken from Engineering Computer Graphics Laboratory, 1998)

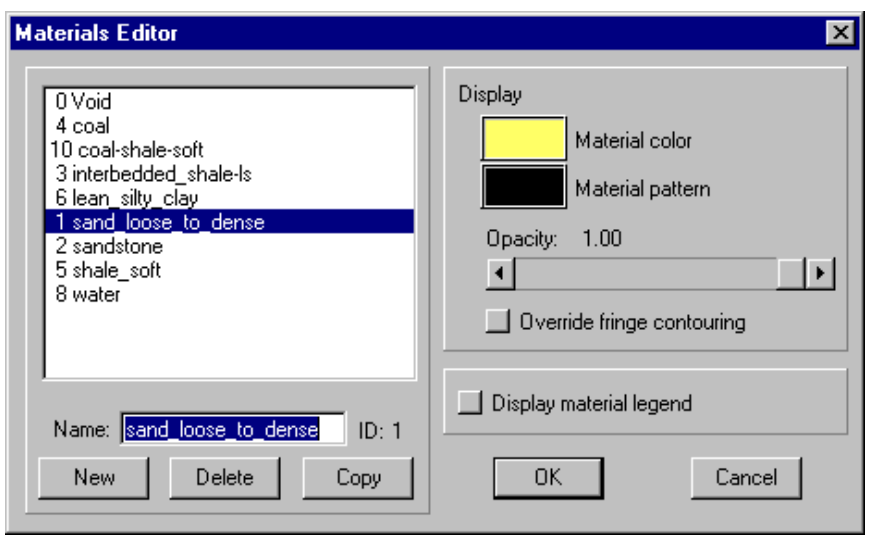


Figure 3.7. Materials Editor dialog box used to define display attributes of each material.

4. Lexington Site Computer Models

A series of three-dimensional computer models were developed for the Lexington site using the GMS software modeling tools. Several models were developed to demonstrate the importance of considering the level of detail in developing three-dimensional computer models. The models developed demonstrate a range of potential refinement of geologic models from a simple soil-rock model to show the soil-rock contact surface to a refined model of the complete site. In this section, the general site conditions for the Lexington Bridge site are described along with a description of the data provided from boring logs produced by MoDOT. The procedures used for developing solid models of the Lexington Bridge site are presented and criteria for simplifying the models and selecting key geologic features are presented. Finally, the models developed are presented.

4.1 Lexington Site

The Lexington Bridge Site is located on the Missouri River near Lexington, Missouri spanning both Lafayette and Ray Counties. When constructed, the bridge will have a total span of approximately 1250 m from the south abutment located in the bluff on the south side of the river to the north abutment located 700 m north of the river in the floodplain. The site geology generally consists of alluvial materials overlying bedrock. Alluvial materials consist of loose to very dense sand with smaller amounts of clay and silty clay. Surficial materials in the area of the southern abutment are primarily of loessial origin (wind blown silt with varying amounts of clay). The bedrock is sedimentary rock of the Marmaton and Cherokee Groups composed primarily of shale with interbedded layers of limestone and coal. Sandstone is also present over a small portion of the site. Several abandoned mine openings from previous coal mining activities are present near the south abutment.

4.2 Characteristics of Geologic Data

All models developed for this project were derived from boring logs provided in the Geotechnical Investigation Report for the Lexington Bridge Project (HNTB, 1998). The site investigation program was performed by MoDOT during the period March, 1996 to June, 1998. Site investigation activities were performed in three phases. The first phase of boring activities was performed in March and April of 1996 and included borings B-1 through B-7 and Abut-1 and Abut-2. These borings were distributed along the entire alignment of the bridge for the purpose of preliminary design and feasibility studies. Boring depths for borings B-1 through B-7 ranged from 6 to 45 meters. Borings B-8 through B-15 were drilled in October-December 1996. These borings are generally located in or near the river. Depths of borings B-8 through B-15 ranged from approximately 32 to 45 meters. Several shallow "test holes" were also made in the second phase of drilling to delineate riprap near the north bank of the river. The final phase of drilling was performed in the period January-June, 1998. This phase consisted of a total of 53 borings (at the time of the Geotechnical Investigation Report) made across the entire site to develop refined knowledge of site conditions. Depths of borings in the final phase of the site investigation ranged from 6 to 45 meters.

Results of laboratory and field tests were provided on the boring logs. Field test data provided included Standard Penetration Test (SPT) results for the overburden materials, unconfined compressive strength (q_u) from pocket penetrometer tests for cohesive materials, and Rock-Quality Designation (RQD) and Core Recovery values for selected rock core specimens. Laboratory test data provided in the boring logs included Atterberg limits and general classification indices for overburden materials as well as unconfined compressive strengths (q_u) from laboratory unconfined compression tests on selected rock core specimens.

Coordinates for borings were provided in station and offset coordinates based on the planned alignment of the centerline of the bridge. True layout in actual coordinates was therefore not possible. All models do not precisely depict actual coordinates for borings but rather station and offset locations from the centerline of the bridge. Boring coordinates can be modified if and when actual coordinates are updated.

4.3 Modeling Process

The basic steps taken in developing the three-dimensional models for the Lexington Bridge site include the following:

1. Reviewed all boring logs, site plans, and geologic descriptions from Geotechnical Investigation Report
2. Identified key materials in geologic profile
3. Interpreted and simplified boring log descriptions into key geologic units
4. Input boring data in GMS
5. Developed preliminary "profile surfaces" defining contacts between geologic materials
6. Refined boring interpretations and profile surfaces based on preliminary surfaces
7. Created basic solids representing geologic units
8. Refined solids using set operations
9. Developed graphics for display and reporting

Development of three-dimensional computer models was, and should be considered to be an iterative process whereby a crude form of the model is initially developed followed by successive and repetitive refinement of the model based on information or inconsistencies that arise during model development. In developing the models described below, over thirty versions of models were developed. The models presented below generally represent final versions of the models developed with varying levels of refinement.

4.4 Selection of Important Geologic Strata

Development of a single model that effectively represents all aspects of a geologic site is tremendously difficult if not impossible. Excessive detail in a model will often cloud critical features and detract from the real purpose of the model. As a practical matter, a model consisting of more than 10 to 15 different materials will tend to be difficult to decipher. In addition, an effective model for one purpose, e.g. a design model, may not be effective for other purposes, e.g. a model used to derive cut and fill quantities. A critical step in developing a model is therefore to consider what aspects of the site are to be modeled and what features will be emphasized based on consideration of the uses of the models. In many cases it is likely that a series of models may be developed for different purposes to illustrate and emphasize different geologic features of a site. As an example, one can imagine development of "design" models that represent a conservative interpretation of the site for the purpose of design of foundations, slopes, or abutment structures. Such design models should focus on the materials, features, and properties that are critical for design. Separate "construction" models might be also developed that represent the "best estimate" of actual conditions with a focus on aspects related to construction such as classifying materials into excavation classes, pile driveability, etc. Additional models could be developed for scour analyses, groundwater studies, borrow suitability studies, or shallow foundation design.

The computer models presented below represent several alternative levels of abstraction. In developing these models, geologic strata were selected based on different levels of model refinement. Specific criteria used for each model are described in detail below. In general, a conservative "design type" approach was used for all models in the sense that weak or compressible strata were generally taken to be "worst case" scenarios.

4.5 Computer Models

A series of three-dimensional computer models was developed for the Lexington site using the GMS software modeling tools. Several models were developed to demonstrate the importance of

considering the level of detail in developing three-dimensional computer models. Specifically, the developed models include:

1. A simple "soil-rock" model for the entire site
2. A refined model of the river crossing area
3. A refined model of the entire site

The models developed demonstrate a range of potential refinement of geologic models.

4.5.1 Soil-Rock Model for Entire Site

The first model developed was a simple soil-rock model for the entire site. In this model, all overburden materials consisting of sands, clays, and silty clays were classified as "soil" and all bedrock materials (shale, limestone, sandstone, and coal) were classified as "rock" (Table 4.1). The developed soil-rock solid model is shown in Figures 4.1 through 4.3. This model represents the lowest level of solid model in that the geologic materials are separated into only two different categories. The model does convey valuable information to users and may be extremely useful for preliminary design or constructability studies or evaluations. This type of model represents the least level of effort required for developing a three-dimensional computer model of a geologic site and should generally be used as a first step in any modeling procedure.

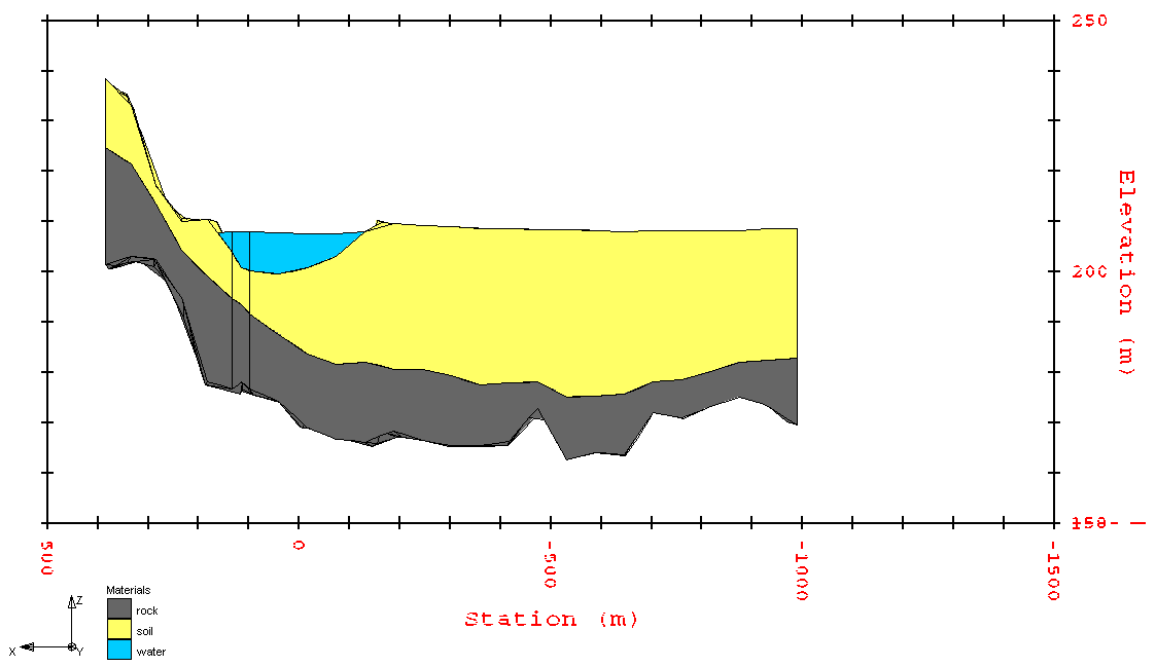


Figure 4.1. Horizontal view of solid model for simple soil-rock model of Lexington Bridge Site. Vertical exaggeration = 10.

Table 4.1. Summary of basis and criteria for establishing material categories for simple soil-rock model of entire site.

Material Category	Basis for Category	Material Descriptions and Criteria
soil	boring log descriptions	all material described as clay or sand; including brown to dark brown lean clay and fine to coarse grained, loose to very dense sand with varying amounts of gravel
rock	boring log descriptions	all material described as shale, limestone, coal, or sandstone varying in stiffness from soft to very hard

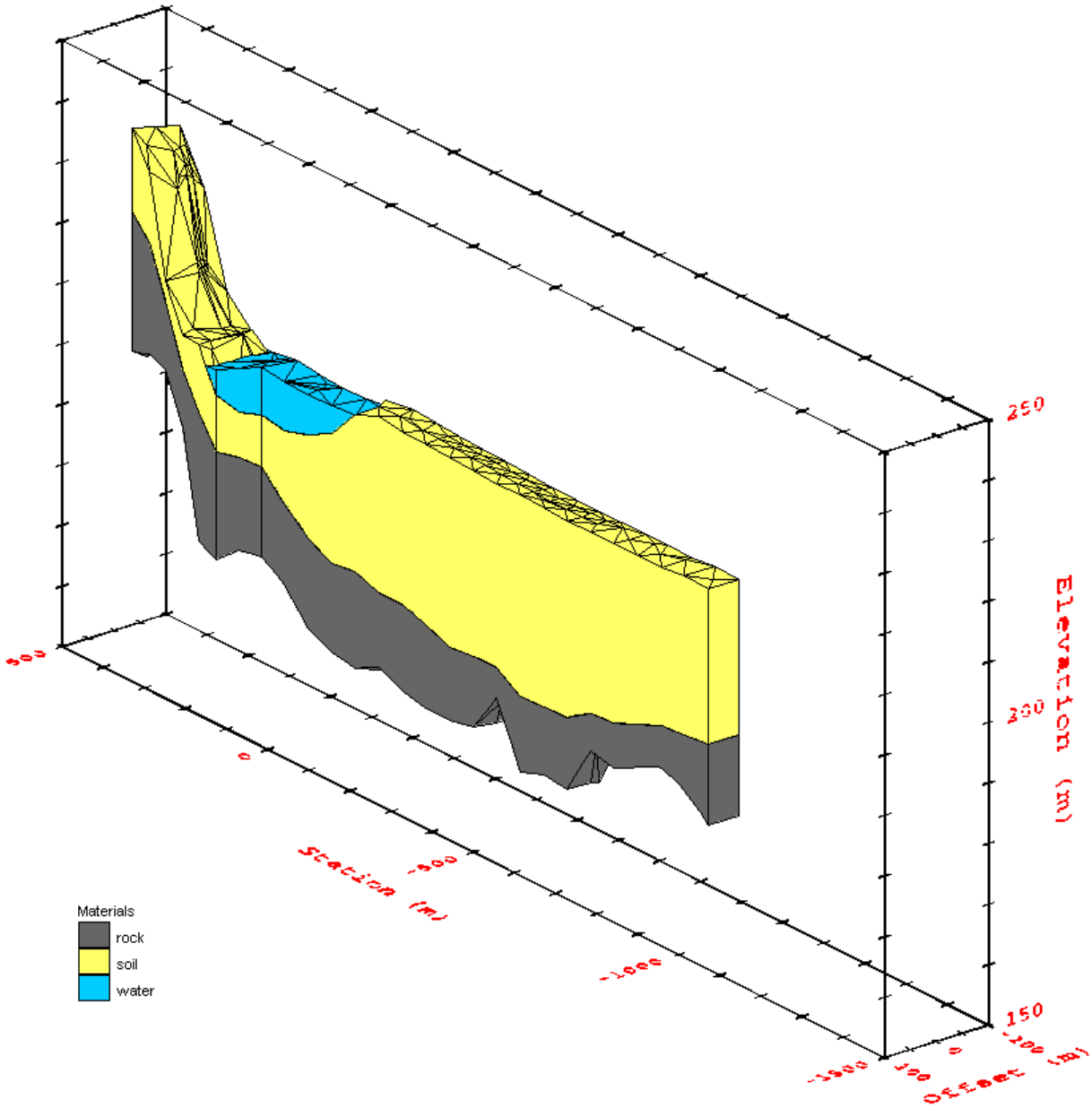


Figure 4.2. Inclined view of simple soil-rock solid model for Lexington Bridge site. Vertical exaggeration = 10.

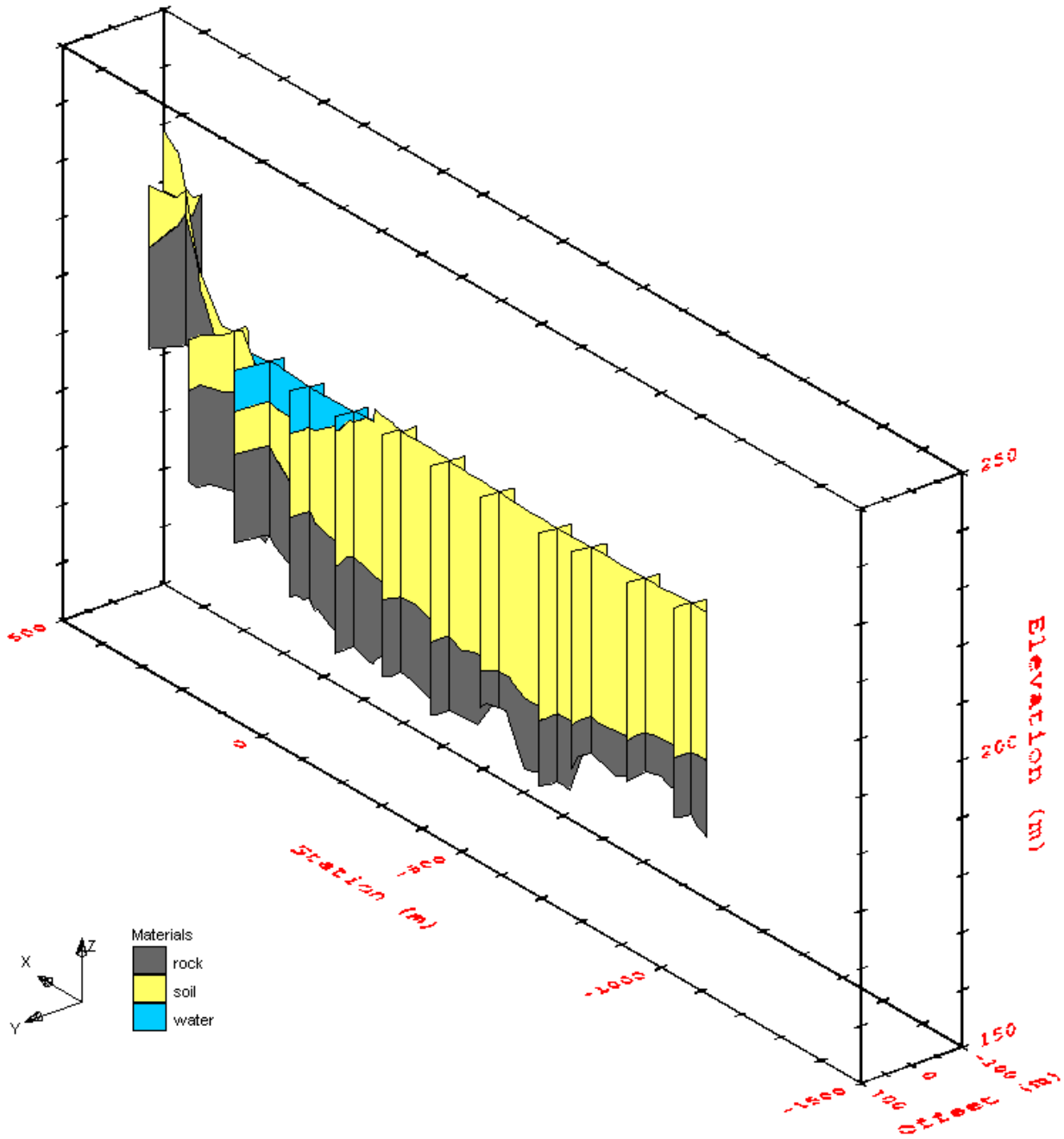


Figure 4.3. Inclined view of cross-sections through solid model for simple soil-rock model of Lexington Bridge site. Vertical exaggeration = 10.

4.5.2 Refined Model for River Pier Area

The second model developed was a refined solid model of subsurface conditions in the river crossing area. The model is shown in Figures 4.4 through 4.7. Figure 4.4 shows an inclined view of the complete solid model. Figure 4.5 shows an inclined view of the solid model with overburden materials removed to emphasize bedrock materials. Figures 4.6 and 4.7 show an inclined view and horizontal view of cross-sections taken through the complete solid model respectively. The model represents an additional level of refinement over the simple soil-rock model in that overburden materials were separated into "sand" and "clay" materials and that bedrock was separated into several different units. The material categories used and the criteria for establishing the different geologic units for this model are summarized in Table 4.2. The material categories were established primarily based on boring log descriptions with some combining of variable materials to provide clarity in the model (e.g. loose sand was not distinguished from dense sand). The model does serve as a clear depiction of a critical portion of the site and serves as an example of a typical refined model over a small area. Models for more limited areas can also be developed from the overall model to provide insight into isolated features of the site or structure as shown in Figures 4.8 and 4.9.

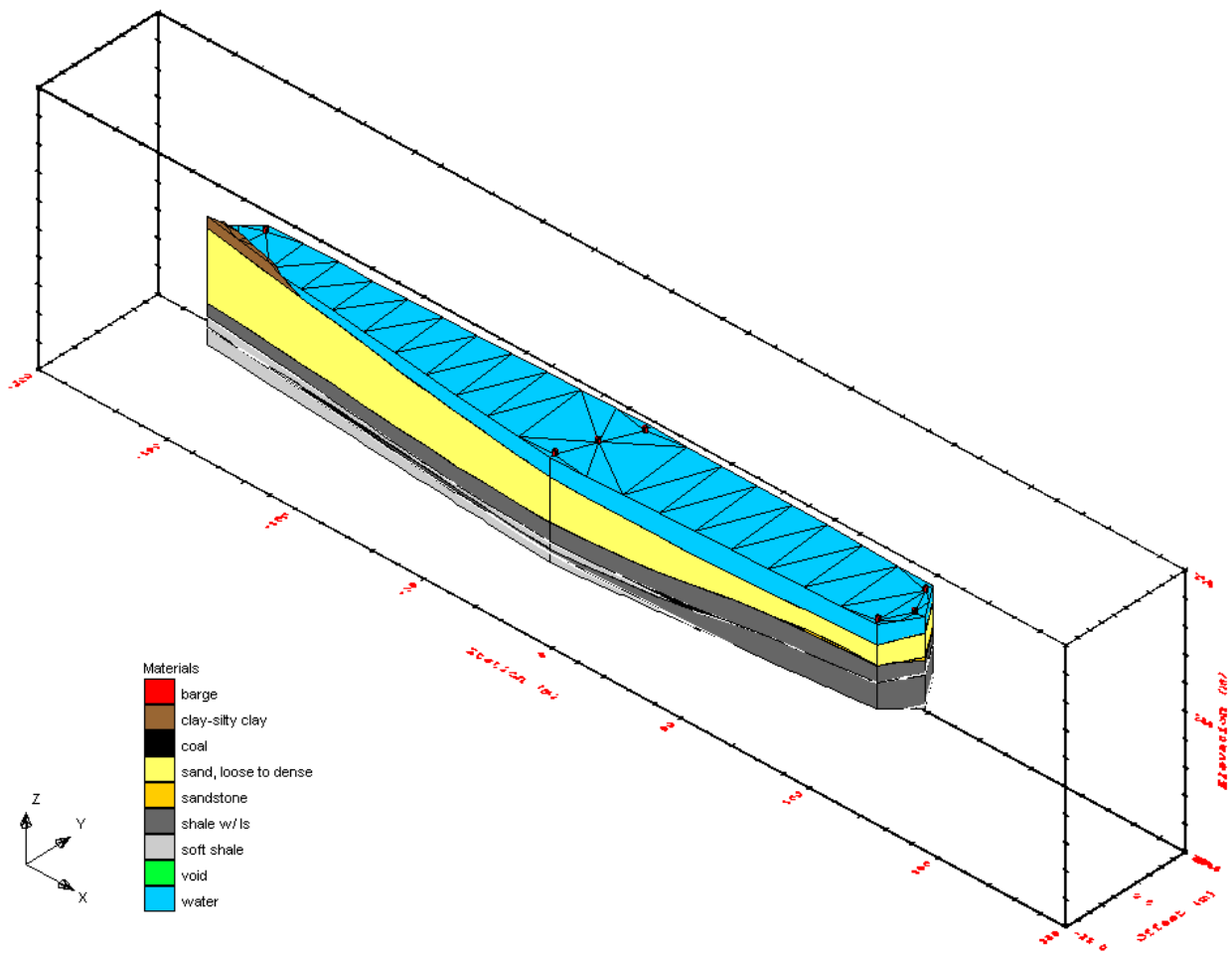


Figure 4.4. Inclined view of solid model for refined model of river crossing area.

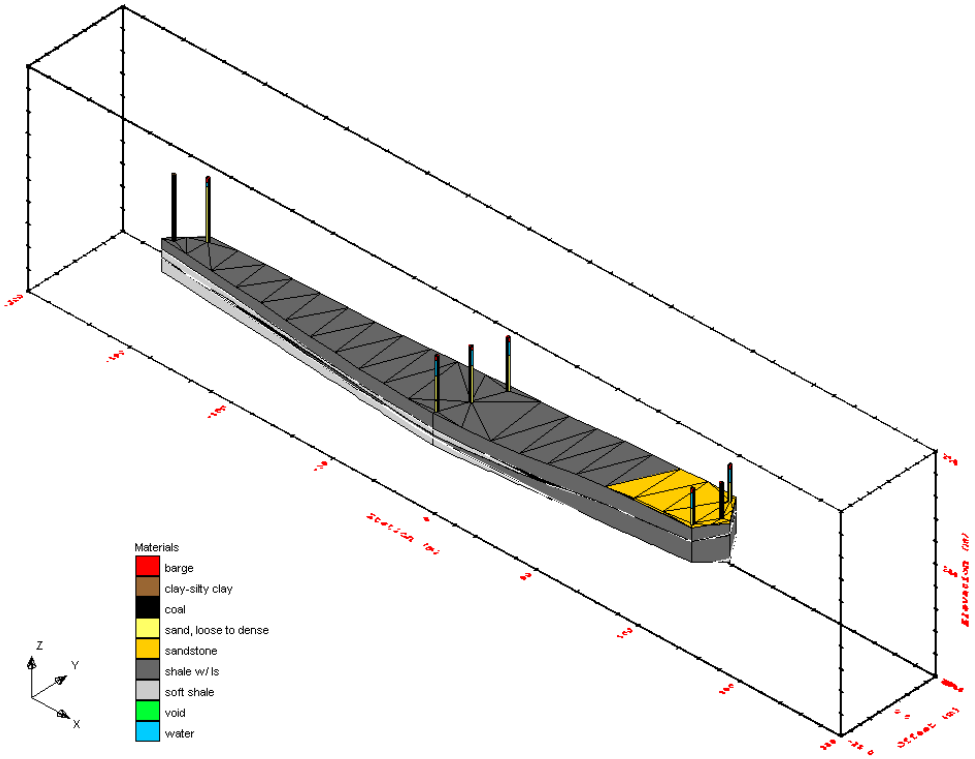


Figure 4.5. Inclined view of solid model for refined model of river crossing area with overburden material solids removed.

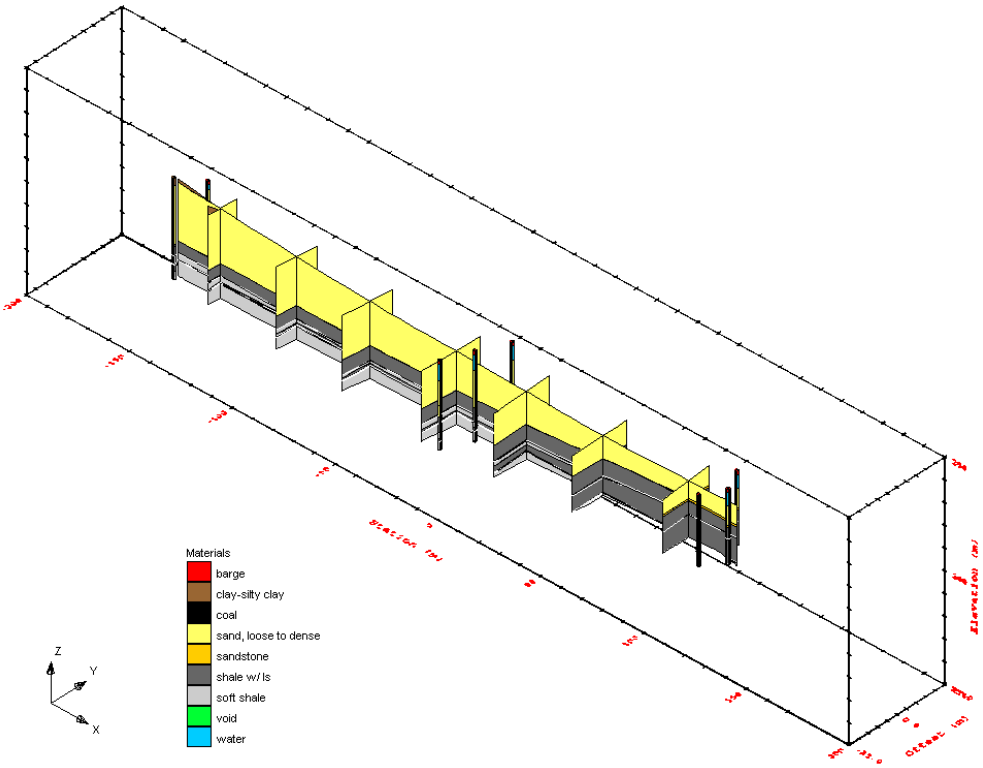


Figure 4.6. Inclined view of cross-sections through refined solid model of river crossing area.

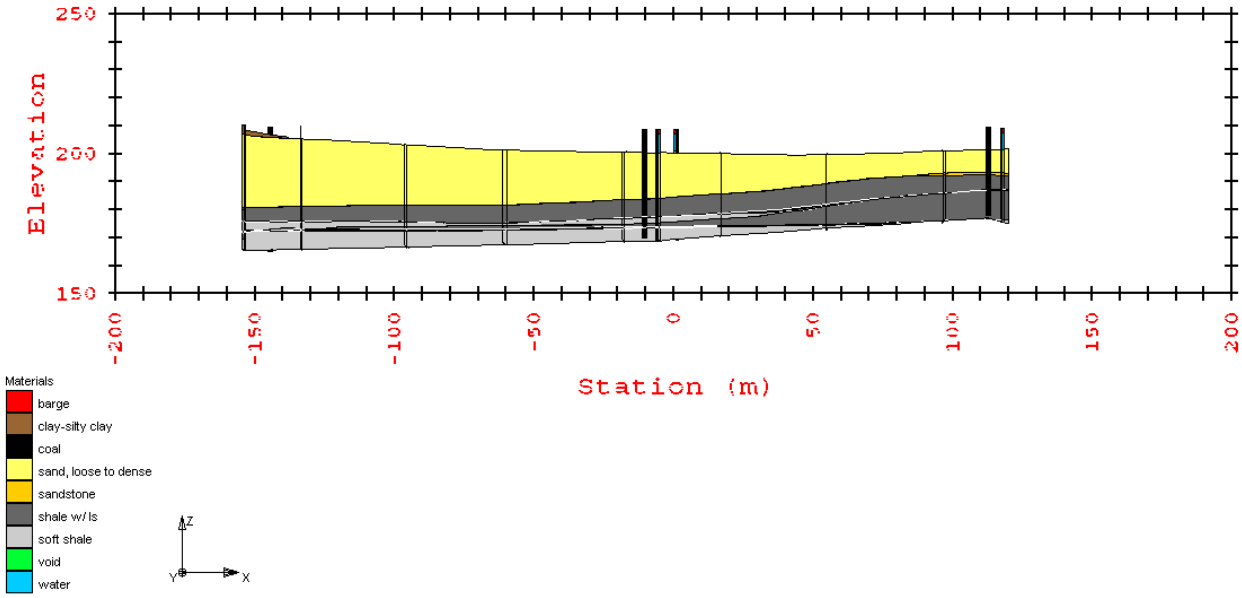


Figure 4.7. Horizontal view of cross-sections through refined model of river crossing area.

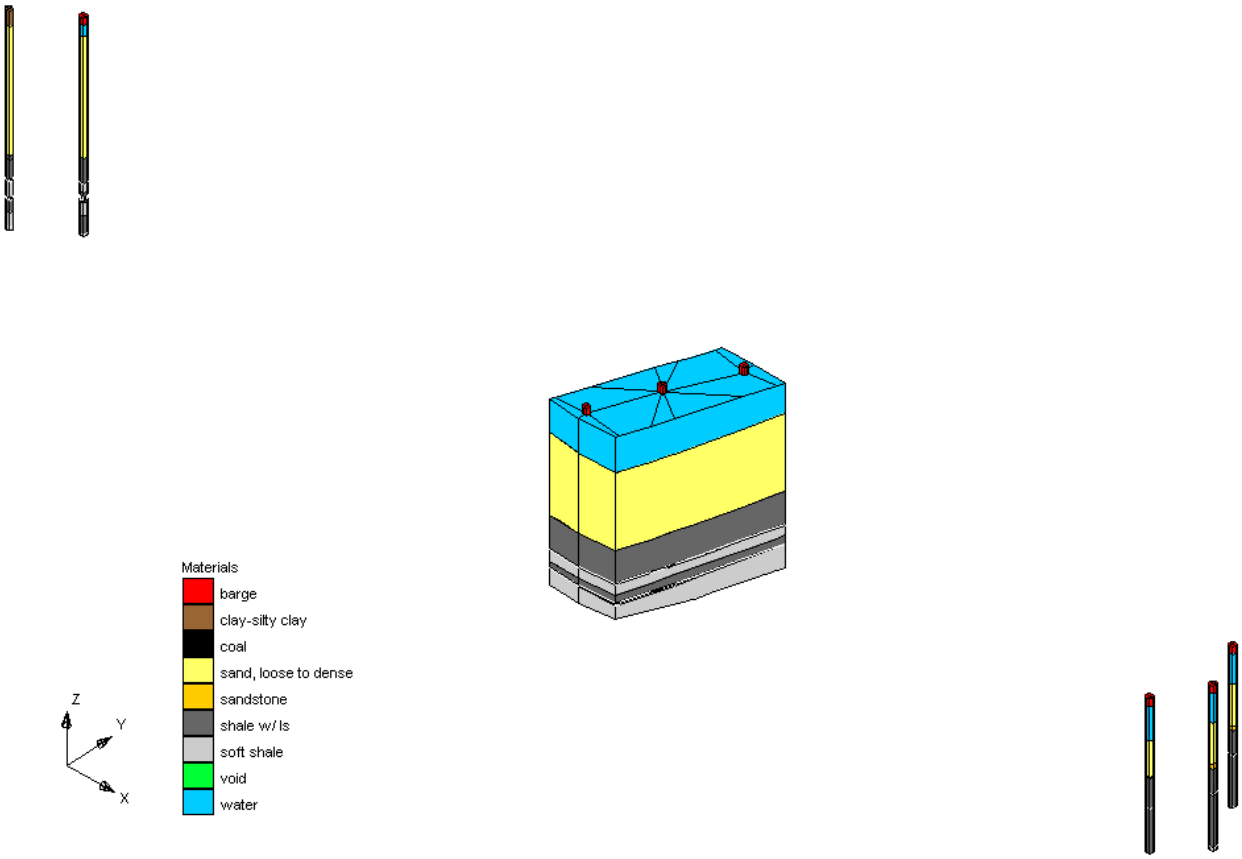


Figure 4.8. Inclined view of river crossing area with isolated solid model of Pier 21.

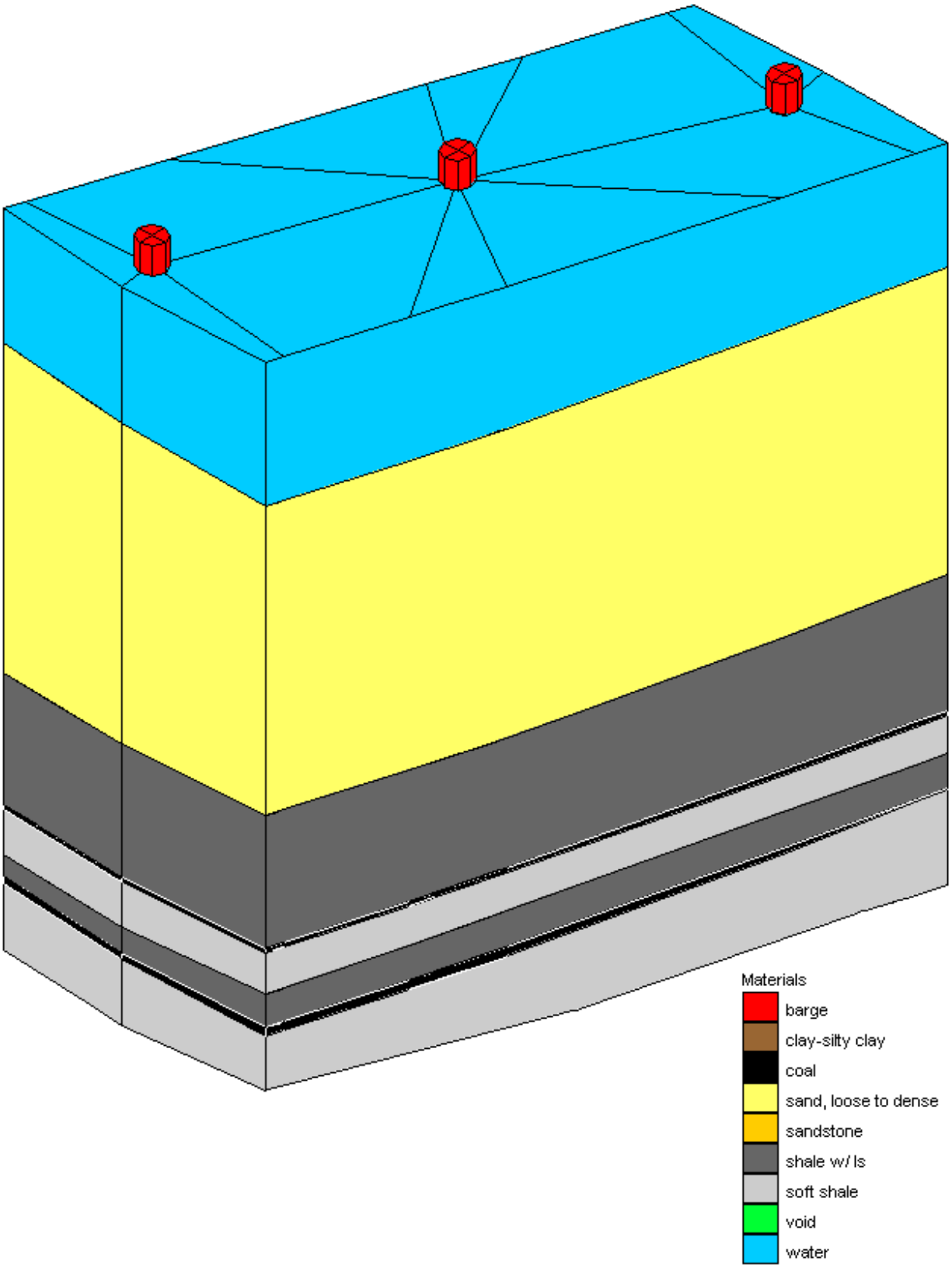


Figure 4.9. Close up inclined view of solid section for Pier 21.

Table 4.2. Summary of basis and criteria for establishing material categories for refined solid model of river crossing area.

Material Category	Basis for Category	Material Descriptions and Criteria
clay-silty clay	descriptions	all material described as clay – brown to dark brown lean clay
coal	descriptions	all material described as coal
sand, loose to dense	descriptions	all material described as sand – loose to very dense, fine to coarse grained sand with varying amounts of gravel
sandstone	descriptions	all material described as sandstone
shale w/ ls	descriptions	all material described as hard shale including that with small amounts of interbedded limestone
soft shale	descriptions	all material described as soft shale without confirmatory laboratory strengths

4.5.3 Refined Model of Entire Site

The final model developed is a refined model of the entire site. The model is the most refined of all models developed and represents a reasonable maximum degree of refinement for a single model. Primary emphasis of the model is on characterizing the bedrock materials for use in design of deep foundation members. The material categories chosen for the model are summarized in Table 4.3. Overburden materials were simply divided into "sand" and "clay" categories whereas bedrock materials were classified into six different categories based on boring log descriptions and results of laboratory and field strength tests. Despite the relatively high level of refinement in the model, it was still necessary to combine some materials with similar strength properties to provide clarity in the model. Other models with similar refinement could be developed to emphasize other features of the site, e.g. a model to emphasize the variability of soil properties for shallow foundation design. The final version of the refined model of the entire site is shown in Figures 4.10 through 4.17.

Table 4.3. Summary of basis and criteria for establishing material categories for refined model of entire site.

Material Category	Basis for Category	Material Descriptions and Criteria
clay-silty clay	descriptions and classification tests	all material described as brown to dark brown lean clay confirmed by laboratory classification tests
coal	descriptions	all material described as coal
coal-shale, medium	descriptions and lab and field strength tests	coal overlain or underlain by medium soft shale as confirmed by laboratory strength tests (500 kPa ≤ q_u ≤ 1000 kPa)
coal-shale, soft	descriptions and lab and field strength tests	coal overlain or underlain by soft shale as confirmed by laboratory strength tests (q_u ≤ 500 kPa)
sand, loose to dense	descriptions	all material described as sand including loose to very dense, fine to coarse grained sand with varying amounts of scattered gravel
sandstone	descriptions	all material described as sandstone in boring logs
shale w/ ls	descriptions and lab and field strength tests	predominantly hard shale with small amounts of interbedded limestone as confirmed by laboratory strength tests (q_u ≥ 1000 kPa)
soft shale	descriptions	all material described as shale soft without confirmatory laboratory strengths

It is important to note that several model "materials" actually represent combinations of materials that have been combined to simplify the model. For example, the "coal-shale, soft" material is composed of adjacent layers of coal and shale. These materials were combined for modeling purposes because

they present similar characteristics for design purposes (low strength). All sand was also considered as a single material (despite the observed range in densities) because the sand is not considered as an important feature for design of deep foundations using current design procedures. Changes to design procedures may necessitate further refinement of the model for the sand materials.

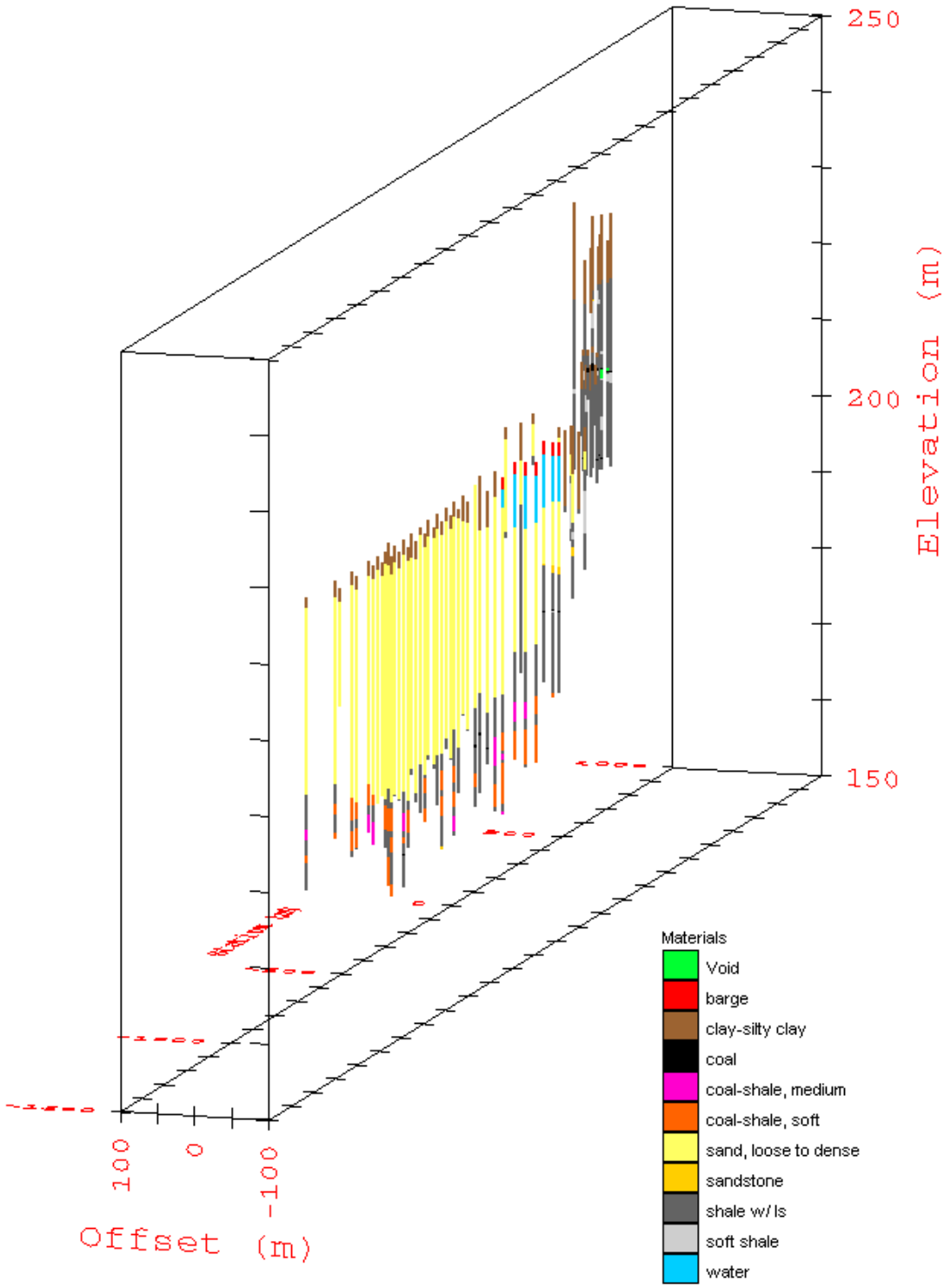


Figure 4.10. Perspective view of borings for Lexington Bridge Site model. Vertical exaggeration = 10.

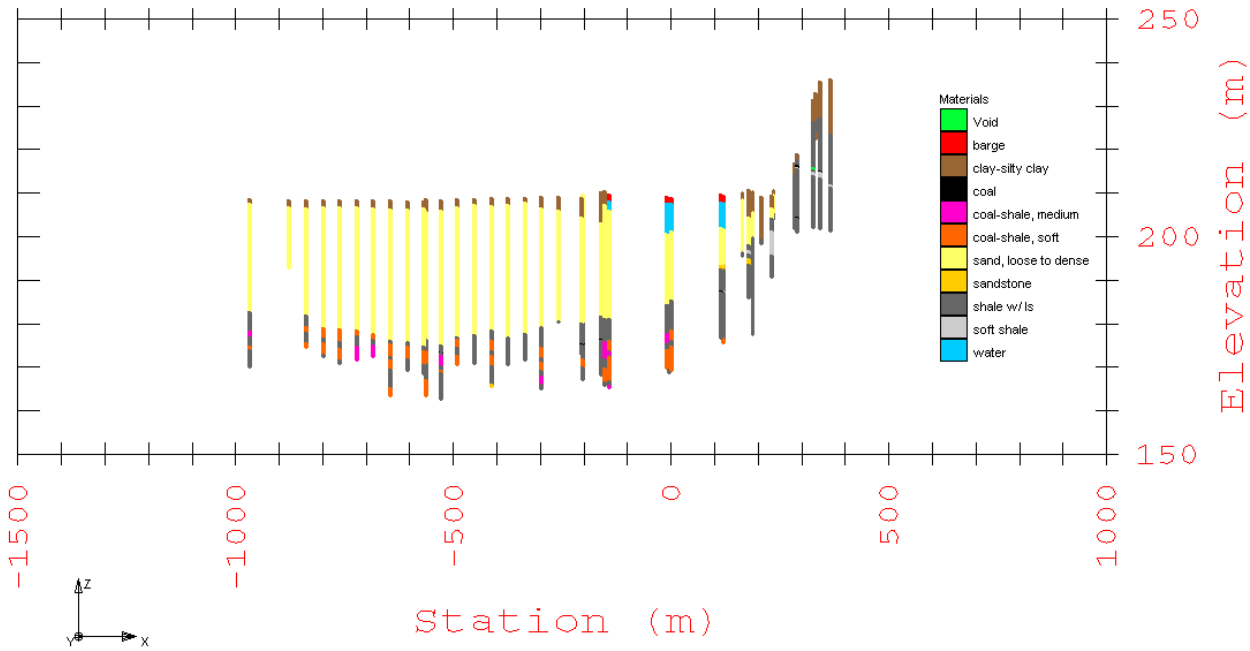


Figure 4.11. Horizontal (x-z) view of borings for Lexington Bridge Site model. Vertical exaggeration = 5.

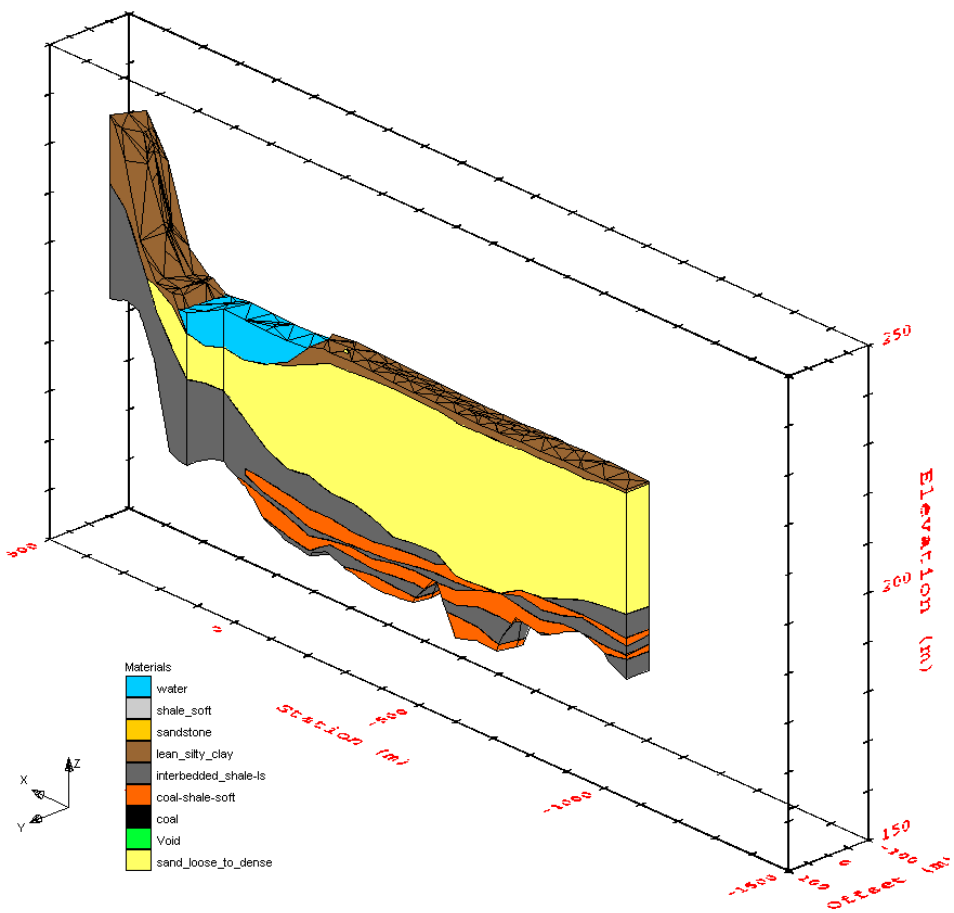


Figure 4.12. Inclined view of solid model for refined model of entire site. Vertical exaggeration = 5.

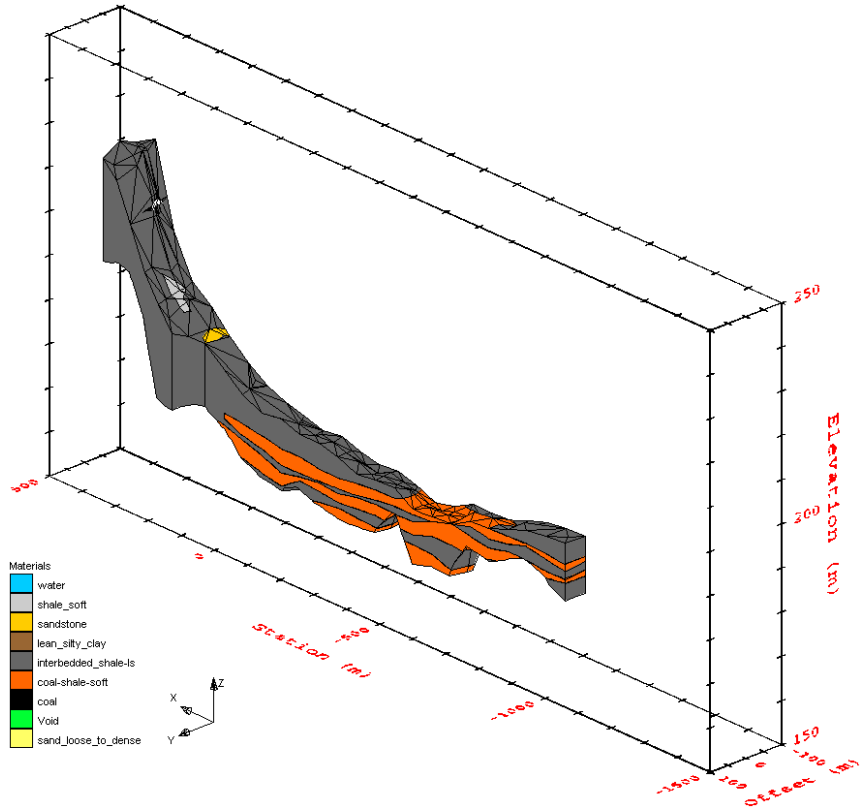


Figure 4.13. Isolated view of solids representing rock materials in refined model of entire site. Vertical exaggeration = 5.

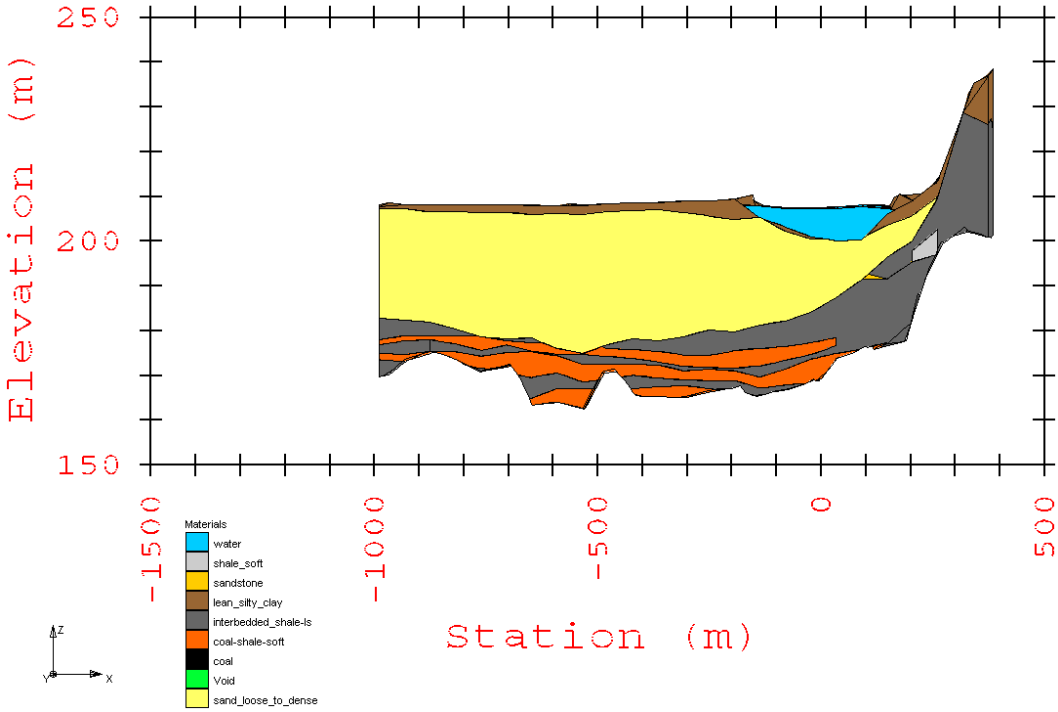


Figure 4.14. Horizontal view of solid model for refined model of entire site. Vertical exaggeration = 5.

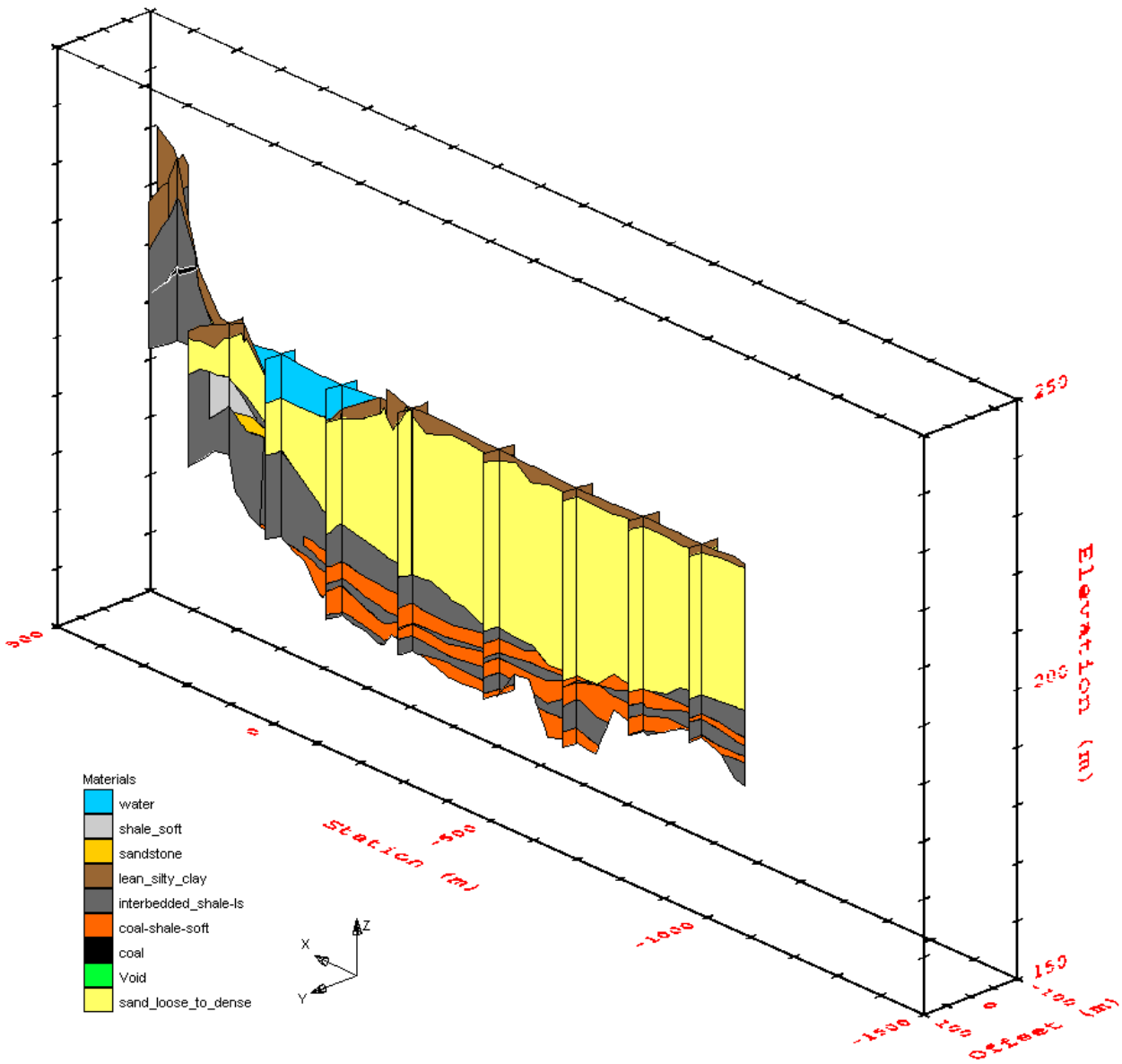


Figure 4.15. Inclined view of cross-sections through refined solid model of entire site. Vertical exaggeration = 5.

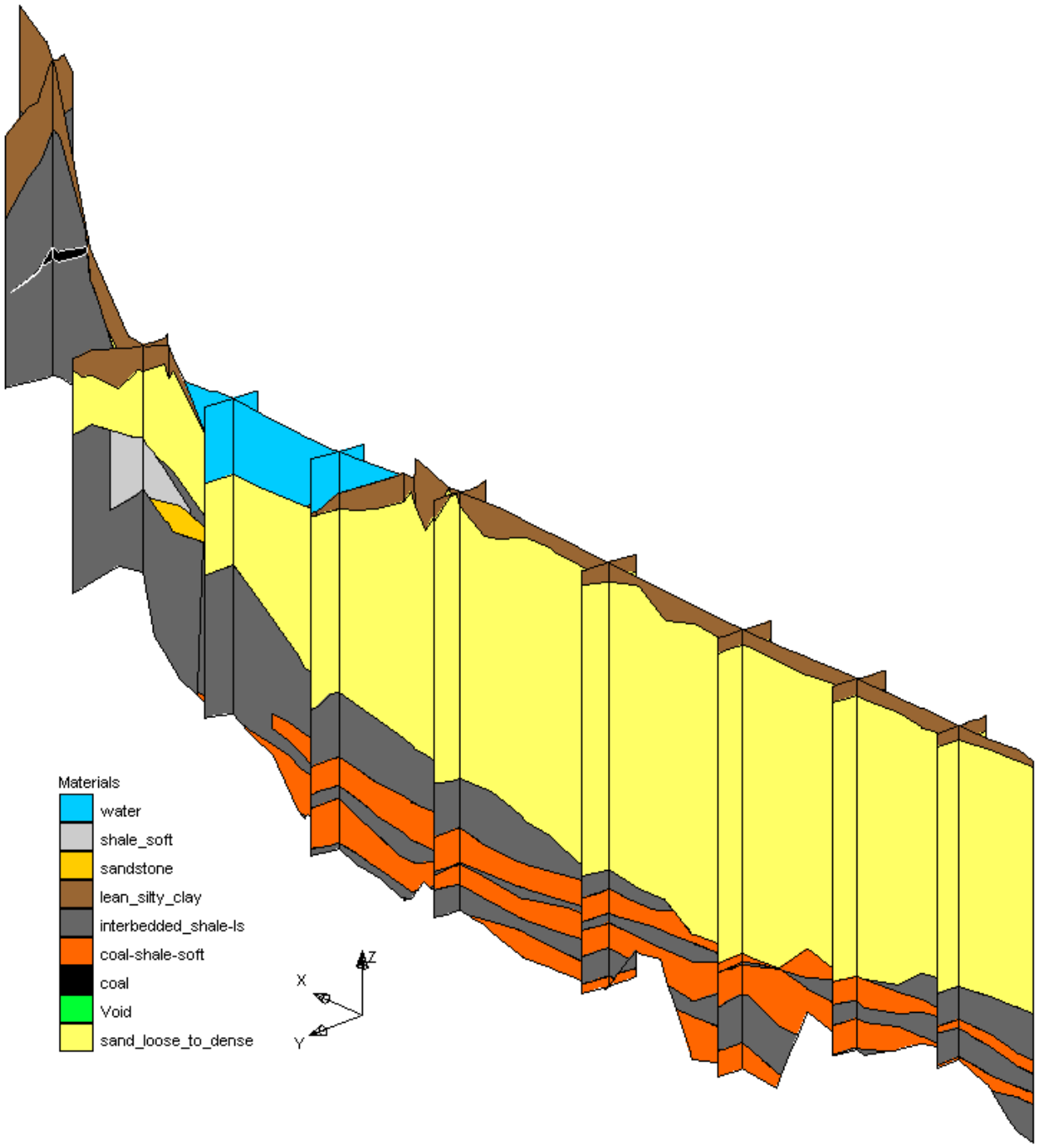


Figure 4.16. Inclined view of cross-sections through refined model of entire site. Vertical exaggeration = 5.

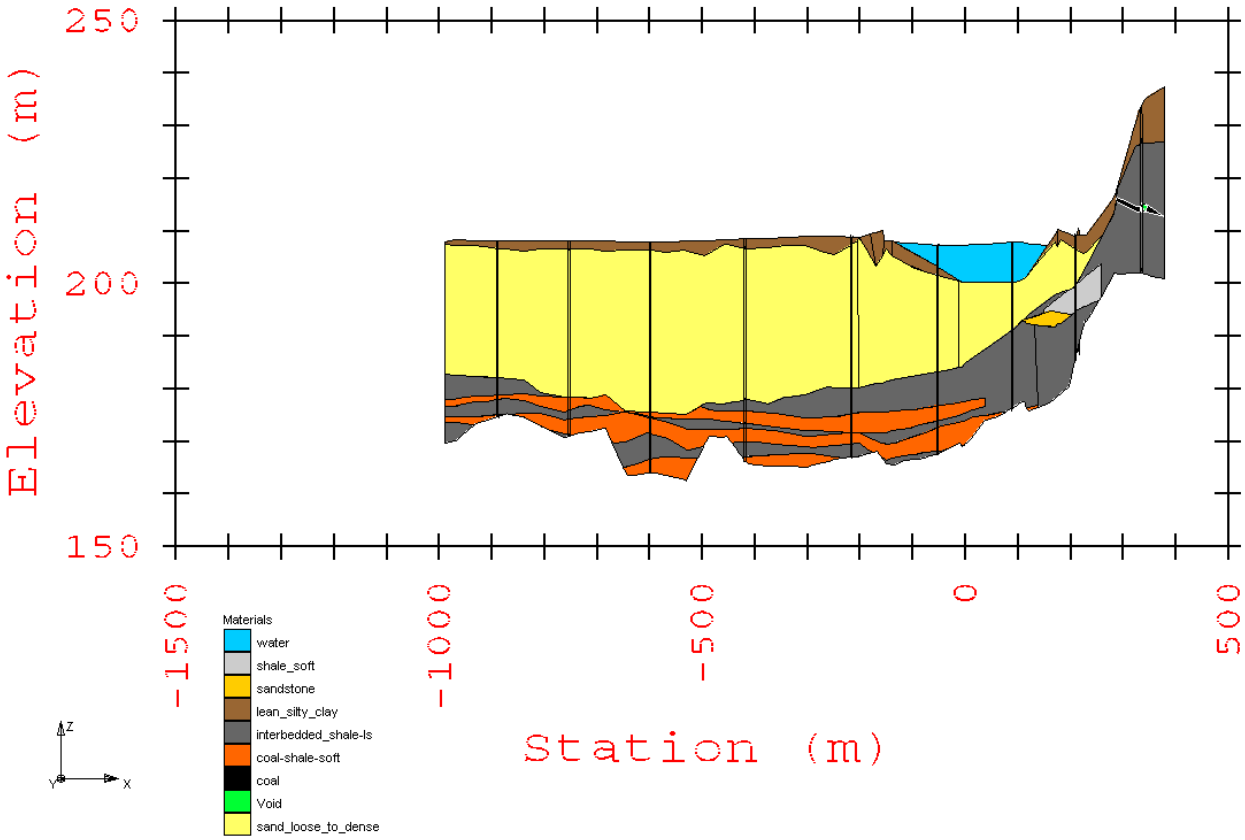


Figure 4.17. Horizontal view of cross-sections through refined model of entire site. Vertical exaggeration = 5.

4.5.4 Comparison of Models

Two different classes of models are shown in Figures 4.10 through 4.17. The simplest form of model generated is a three-dimensional model of all borings as shown in Figures 4.10 and 4.11. Boring models require no interpolation or extrapolation from the borings themselves and thus represent an accurate depiction of the boring logs and correct spatial relationships among borings. Boring models lack completeness in that users of the model are required to mentally interpolate among borings to interpret site conditions. However, interpretation is greatly facilitated by the ability to interactively rotate, pan, and zoom to observe the three-dimensional model from an essentially infinite number of perspectives. Three-dimensional boring models are further limited by the fact that cross-sections through the model cannot be generated. As a result, some borings are inevitably hidden from view. While viewing the model from different perspectives can reduce this problem, the spatial relationships among borings can become "distorted" in some views leading to misleading or inaccurate interpretations.

The primary advantage of three-dimensional boring models is that they can be developed with relatively little effort. Some interpretation is required, even for boring models, in that the model developer must choose criteria for selecting different materials in the borings. The primary task of model development thus lies in establishing the categories of materials to be modeled. Once these are defined, the boring logs can be marked up and data entry tasks can be performed by non-technical staff. The primary disadvantage of three-dimensional boring models is that the burden of interpretation and interpolation is placed on the users of a model rather than on the developer of the model. Development of a three-dimensional boring model is a requisite task prior to developing solid models.

The second class of model is a complete solid model of the site. Solid models are developed directly from boring models by creating interpolated surfaces to conform to the contacts on all borings. While the level of effort for developing solid models is significantly higher than that required for developing

a boring model, solid models permit a complete interpretation of site conditions to be graphically conveyed. Solid models can also be viewed from an essentially infinite number of perspectives and can be manipulated to emphasize different parts of the model as shown in Figures 4.12 through 4.14. Cross-sections can also be taken through any plane of a solid model to display features that are internal to the solids (e.g. the mining cavity for the Lexington site) as shown in Figures 4.15 through 4.17.

The principal advantage of solid modeling, as compared to simple boring models, is that the resulting model will represent the interpreters best estimate of site conditions over the entire site (not just at boring locations). The resulting model will necessarily arise out of some interpolation between borings and extrapolation in areas without borings thereby introducing some uncertainty into the modeling process. However, it places the burden of interpretation on personnel that have specialized skill and experience in geologic interpretation rather than on other personnel that may lack such skills.

5. Key Issues for 3-D Computer Modeling of Subsurface Conditions

Several critical issues for further implementation of 3-D computer modeling were identified during development of the three-dimensional computer models for the Lexington site. These issues include addressing known sources of uncertainty, methods for reporting and displaying three-dimensional models and transferring information to potential users, and contracting ramifications.

5.1 Sources of Uncertainty

Interpretation of geologic sites is fraught with uncertainty. The amount of information obtained from a typical site investigation is remarkably small despite the importance of geologic conditions on the overall design, performance, and cost of a structure. Three-dimensional modeling does not eliminate uncertainty. However, the process of developing computer models and perhaps the models themselves often lead to *identification* of sources of uncertainty. Once identified, the sources of uncertainty can be directly addressed through additional site investigation or laboratory testing or at least considered and understood in the design process. In addition, three-dimensional computer models can reduce discrepancies associated with lack of adequate understanding of geologic conditions (including uncertainties) by those not involved in the site investigation and interpretation process.

The primary sources of uncertainty encountered in developing the computer models for the Lexington site include the following:

1. Inconsistency among boring log descriptions
2. Lack of a single property for comparing all materials
3. Potential variability and errors in laboratory testing
4. Lack of true coordinates for borings
5. Required interpolation and extrapolation
6. Modeling of transition zones

Each of these issues are addressed in more detail below and several recommendations for reducing uncertainty are presented in the recommendations section of this report

A significant problem that was encountered during development of the computer models was variability and inconsistency among boring log descriptions. This is a natural result of human nature to interpret and perceive qualitative parameters such as stiffness differently. While there are specific criteria for such qualitative parameters, interpretation and application of these criteria remains subjective. Steps are currently being taken by MoDOT Soils and Geology personnel to provide more consistent descriptions of geologic materials. While these steps are likely to improve consistency among different personnel, it is not likely eliminate the problem.

One potential method for reducing the uncertainty associated with boring log descriptions is to rely more heavily on measured material properties when developing geologic models. However, no

single property is generally measured for all materials, thus making direct comparisons among different materials difficult. One possible exception to this statement is that water content is often measured for most samples taken in the field. While water content can be an important parameter to consider in comparing materials for geologic interpretation, the water content of geologic materials can change significantly over time due to changes in environmental conditions, particularly in extensive site investigations performed over a period of months or years. Measured materials properties are also subject to some uncertainty since factors such as sample disturbance, method of testing, and measurement errors can affect measured properties. Relying more heavily on measured properties may also necessitate laboratory testing in excess of what is currently performed which may increase costs for site investigation (such costs may be justified if it leads to better interpretation however).

The most significant source of uncertainty in geology modeling is the requirement that the subsurface geometry be interpolated between borings and extrapolated to areas without borings. This source of uncertainty can obviously not be eliminated. However, the level of uncertainty can perhaps be reduced by using selective placement of borings in areas of highest uncertainty rather than placing borings at prescribed locations for all structures. Such efforts can be greatly enhanced if three-dimensional models are developed during the site investigation process rather than after the fact.

Bridge sites, and in fact many MoDOT sites, are unique in the fact that the sites are characteristically long and narrow owing to the linear nature of the structures. As a result of this fact and current site investigation techniques, borings are generally more closely spaced in directions perpendicular to the centerline of the bridge than they are along the length of the bridge. This results in more refined knowledge of the geologic structure in directions perpendicular to the bridge at selected locations across the bridge (generally at locations of bridge bents). This approach is certainly reasonable since the borings are located at critical locations along the structure. However, it leads to more uncertainty in other areas, which can impact the performance of the structure as well. The real issue is to determine whether it is better to have borings beneath key parts of the structure or whether it is better to reduce the overall uncertainty across the entire site. The long and narrow shape of bridge sites also affects visualization of computer models in that one dimension (the length of the site) tends to overwhelm the others (the width and depth of the site). This problem can be reasonably remedied using vertical exaggeration for the depth dimension and by zooming in on or isolating selected lengths of the site for visualization purposes.

The highest level of uncertainty in the models generally lies in areas outside of the extent of borings and in "transition" zones between different materials. Areas outside of borings require that the geometry and properties be *extrapolated* as opposed to *interpolated* thereby leading to increased uncertainty. In the models described above, all solid models were trimmed at the base to conform to the extent of borings at the site. While not of primary significance, one important part of developing and sharing a model is to convey what is known and unknown about the model. If an arbitrary base were used for the model (e.g. at some common elevation below the base of all borings) the users of model would be left with the impression that the lowest strata continued to the base of the model, and perhaps beyond. In reality, the materials beneath the base of borings are uncertain and thus creation of the model base using the base of each boring accurately represents the extent to which information is known. The model developer is of course free to add interpretation to the base of the model based on experience or additional data and can place the base at any desired location as long as the developer is comfortable and reasonable sure of the material in those locations.

Transition zones represent particularly troublesome geologic features to accurately model. While some geologic contacts are discrete, many contacts are actually gradual transitions from one material to another. One common example encountered is the transition from soil to weathered rock to parent rock. Geologic modeling software is not currently well suited to modeling such transitions as all boundaries are considered to be abrupt. Another type of common occurrence is a "pinch out" where a particular stratum is observed in one or more borings but is not observed in adjacent borings. GMS can model this type of structure but there is often a high level of uncertainty in where the actual pinch out lies.

5.2 Reporting and Visualization of Geologic Models

A critical issue that arises in three-dimensional modeling of all types is how to report and share the information contained in the models. One option is to simply share the models in digital form and allow the users of the model to interactively view the model with the same software used to create the model. This option has the advantage that users can view the model from an essentially infinite number of perspectives, make cross-sections through key parts of the model, and highlight key geologic features. The drawback of this approach is that additional licenses for the software must be acquired to permit viewing of models and additional personnel must be trained to use the software (at least the visualization features).

The other option is to share printed or digital images of the model using selected views. This option obviously limits the views that users can observe and may limit thorough understanding of the models. Costs associated with sharing selected images of a model will likely be less than that associated with sharing digital versions of the models. Specific selected views may be chosen by the model developer. Alternatively, a set of "standard views" may be developed over time as experience with three-dimensional modeling is developed.

5.3 Contracting and Data Transfer Issues

The final issue that arose during the modeling process through meetings with MoDOT personnel is the issue of data transfer to outside contractors. As a government agency, MoDOT is required to provide all information obtained for a project to potential contractors. Three-dimensional computers models developed for a project would be included as part of this requirement. There is therefore the possibility that these models could be used as basis for "changed conditions" claims from contractors if actual site conditions encountered during construction differed from the interpretations develop.

Solid models certainly do introduce an interpretation and therefore may potentially open up the possibility for changed condition claims if conditions encountered during construction are not consistent with those shown in the models. However, the possibility of changes in contracting practice should not be overlooked. It is conceivable that if MoDOT were to develop three-dimensional computer models for subsurface conditions that MoDOT would have to take responsibility for the accuracy of the models. However, removing this responsibility from contractors could potentially reduce bid prices to the extent that modeling would be cost effective. MoDOT would inevitably have to pay for changed condition settlements for some cases. However, the overall effect of this responsibility may be cost effective if costs for several projects are considered together.

Boring models such as the ones presented previously do not introduce any more interpretation than current two dimensional cross-sections or boring logs aside from the potential for errors in inputting data. Development of simple boring models for bridge sites may therefore serve as an intermediate step to evaluate the potential for three-dimensional computer modeling for additional sites without the added expense and potential risk associated with implementing more rigorous three-dimensional solid modeling.

6. Uses and Limitations of 3-D Computer Modeling

Three-dimensional geologic modeling tools have the potential for offering great benefit for design and construction of bridges and other structures. The primary advantage of computer modeling of geologic sites lies in enhancing the interpretation of geologic conditions by providing tools for rapid and effective display and manipulation of large amounts of geologic data and in providing a true visual "picture" of the subsurface. Once a solid model is developed, the software allows viewing of the overall model from an essentially infinite number of perspectives and provides tools for viewing the "insides" of the model by viewing cross-sections or hiding one or more geologic strata to view key portions of the model. The three models of the Lexington Bridge site presented above demonstrate the current capabilities of geologic modeling software tools for developing a realistic interpretation of geologic sites and for conveying that interpretation to others. The models also demonstrate a range of potential degrees of refinement of computer models that may be used for different applications and purposes.

Some caution on the use of computer models is also warranted however. Like any software tools, the opportunity exists for abuse or misuse of computer models of geologic sites. The primary risk associated with use of computer models is flat out acceptance of a model as being reality. A model is, by definition, on an interpretation of reality. Development of computer models is no substitute for additional borings and laboratory testing to further define a geologic site. Computer modeling can, however, improve the effectiveness and efficiency of additional borings by helping to identify locations of the highest uncertainty.

Three-dimensional geology models are also not well suited to all sites. Geologic models cannot be created without a minimum of at least three borings. As a practical matter, at least four borings are required and a more realistic number is on the order of about 8 to 10 borings. In addition, development of a three-dimensional model necessitates that borings must not be collinear (lying along a single line).

Additional uses for three-dimensional modeling also exist. With currently available tools, it is possible to develop three-dimensional models that represent conditions for all stages of design and construction. The models developed for this project could be modified to include excavations and fills for approach embankments, excavations for bridge piers or other structures, or to represent the riverbed when subjected to several different scour events. In this mode, the three-dimensional models become an extremely effective tool for design, estimating and construction. Relatively crude models based on a limited number of borings could serve for preliminary design purposes while more refined models could be developed for final design and analysis. Models could be used for cost estimating purposes by using the models for estimation of cut and fill quantities or locations of suitable borrow sites. Finally, three-dimensional models could assist during construction by providing a consistent interpretation of expected field conditions throughout the site. Geologic models could also be updated during construction as actual conditions are revealed (e.g. from pile driving records, excavations, etc.) to provide valuable information and enhancements to the developed models.

7. Summary of Geologic Modeling Software Packages

Several other software packages are also available for three-dimensional geologic modeling. While the list of available software packages for geotechnical modeling is extensive, only a relatively small number have capabilities for true three-dimensional modeling similar to the capabilities used in this project. A summary of these software packages and their capabilities is shown in Table 7.1. All of the listed products are modular in nature and the exact capabilities and prices depend on the modules purchased. Techbase and Lynx are primarily Unix based software packages that are designed for highly intensive geologic modeling associated with the mining industry (Smith, 1999). Both of these software packages can be used for more traditional geotechnical modeling but have a steep learning curve. Both have the general capabilities available in GMS with the addition of capabilities for storing geologic properties in a database associated with a model. Rockworks is a Microsoft windows based package that has some of the general capabilities of GMS. However, Rockworks solid modeling is severely limited when compared to the other products listed. The GMS user interface is clearly superior to the interfaces of the other products in terms of real time interactive viewing of models. Several add-on packages for popular CAD or GIS programs are also available, but none have capabilities that approach the listed products.

Table 7.1. Summary of capabilities of available geologic modeling software.

Product	Interactive 3-D Viewing	Borehole Modeling	Surface Models	Solid Models	Cross-sections	Material Property Database	Drill Log Production
GMS	Yes	Yes	Yes	Yes	Yes	No	No
TechBase	No	Yes	Yes	No	Yes	Yes	Yes
Lynx	Yes	Yes	Yes	Yes	Yes	Yes	No
Rockworks	No	Yes	Yes	No	Yes	No	Yes

8. Potential Applications of 3-D Modeling – A Vision of the Future

Use of three-dimensional modeling is only one key component of site investigation and interpretation. However, many exciting possibilities exist for improving the quality of site investigation activities through the use of three-dimensional subsurface models. The use of three-dimensional models has the potential to revolutionize the way that site investigations are planned and performed by intimately linking the model development and site investigation activities. One can imagine developing a three-dimensional model in the field during boring and sampling activities wherein field personnel directly input boring data into the computer and develop the model while in the field. The model would initially be very crude, but would be updated in real time or near real time as new borings were being performed. Locations for subsequent borings could be chosen in the field with the full benefit of observing the model as it is being developed. In the not too distant future, there is the potential for real time data acquisition from field tests (e.g. cone penetration tests) that can give field personnel immediate data on soil conditions in the boring (e.g. water content, grain size distribution, stiffness, strength, even visual pictures using the "vision cone"). Global Positioning Systems could be attached to boring equipment to provide accurate three-dimensional coordinates for all borings, both at the surface and below the surface. Geostatistical tools could also be incorporated into the modeling process to assist field personnel in determining what areas of a site have the most uncertainty and decision analysis tools could be used to provide cost-benefit data for deciding whether and where additional borings are warranted. With current remote data transmission technology, boring and model data could also be transmitted to other locations thereby permitting senior personnel to monitor and direct the site investigation process from afar. Laboratory testing activities could also be automated so that specific samples and tests performed in the laboratory could be tracked and linked to the geologic model and boring log drafting tasks could become virtually automated.

Three-dimensional models could also be linked to Geographical Information Systems (GIS) to incorporate underground utilities and other structures (such as the mine openings at the Lexington site). Historical geotechnical data from previous site investigation activities in the area or from field performance data from nearby structures could be incorporated. Data obtained from remote sensing techniques from a variety of sources could also be incorporated with data obtained from boring and sampling to provide additional information on site conditions and how conditions have varied over time.

9. Recommendations for Implementation of 3-D Modeling

Development of three-dimensional computer models of geologic sites clearly shows great promise for enhancing interpretation and information transfer in the near term as well as the potential for dramatically improving overall site investigation activities in the future. Based on the results of this project, it is recommended that three-dimensional modeling activities be expanded to further evaluate the potential benefits of computer modeling of subsurface conditions. In the near term, an expanded pilot program consisting of approximately 3 to 5 additional sites is recommended to evaluate the use of models for a variety of sites in a manner that more closely resembles the process that would be applied in more extensive application of 3-D modeling. Specific recommendations for the expanded pilot program include:

1. The selected sites should have varying characteristics with respect to size, importance and geology.
2. Preliminary model development should make use of historical geotechnical data if it is available. If the opportunity arises, a preliminary model derived entirely from historical data should be developed prior to site investigation activities.
3. Modeling activities for the selected sites should begin prior to, or during field site investigation activities so that the modeling process will more closely resemble the process that would be used in routine application and so the potential for using models to assist boring locations can be evaluated.
4. Models should be developed to represent conditions before, during, and after construction to evaluate their use for conceptual design and analysis and for construction cost estimating.

5. Models should be developed by personnel that are closely involved with field and laboratory site investigation activities.
6. Locations for all borings should be selected on the basis of the results of modeling activities to the extent possible. For example, a series of preliminary borings should be placed around the perimeter of the site (perhaps at the four corners) to allow development of a preliminary model. Subsequent borings should then be placed at locations of the highest uncertainty and the model should be updated as new data is obtained to provide the "latest" interpretation of the site.
7. Construction activities at one or more of the sites should be monitored to evaluate how closely the model conforms to actual conditions encountered during construction and to develop additional potential uses for three-dimensional models.
8. Interim versions of all models should be circulated to key personnel throughout MoDOT to permit critical evaluation and input to the modeling process.

The basic procedure for creating models should generally follow the procedure used for this project as described above with modifications as necessary to account for the above recommendations.

In addition to the expanded pilot program, potential systems for storing field and laboratory test data in geotechnical databases should be evaluated. Several commercial systems are currently available for this purpose. The potential for incorporating geotechnical data in a GIS type of system should also be considered. Currently most GIS systems lack capabilities in storing subsurface data, but new systems appear to be improving in this area. Use of geostatistical techniques for evaluating and representing uncertainty in geologic models and for developing methods for evaluating the costs and benefits associated with additional borings, load tests, or instrumentation should also be considered.

10. References

Engineering Computer Graphics Laboratory (1998), *Groundwater Modeling System – Reference Manual*, Brigham Young University, Version 2.1.

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