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DEVELOPMENT OF ROCK MECHANICS PROPERTIES DATABASE — PROGRESS REPORT

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ABSTRACT

The objective of this report is to document progress to date in development of a rock mechanics properties database. The approach adopted for developing the rock mechanics properties database is to build submodel(s), using EarthVision software and the currently existing three-dimensional (3D) geological framework model for Yucca Mountain, Nevada, developed by the Geology and Geophysics Element of the Center for Nuclear Waste Regulatory Analyses. Rock mechanics properties to be included in the database are intact rock properties, joint properties including information related to joint geometry, rock thermal properties, hydrological properties, and values of parameters necessary for rock mass classifications using the Rock Mass Rating and the Norwegian Geotechnical Institute Tunnelling Quality Index, Q, systems. Rock mass properties can be generated using various relevant properties contained in the database. All four methods in the present version of EarthVision software which were evaluated in this study exhibit difficulties with incorporating and graphically representing the geometry-related properties of joints in the 3D geological framework model. Extensive effort would be required if the present version of EarthVision software were to be used for representing joints in the 3D geologic framework model. Incorporation of an underground excavation in the 3D model is not straightforward. Both methods available in the present version of EarthVision software require an extensive amount of user involvement to define the tunnel. Moreover, it is difficult to develop a map of joint network on the tunnel surfaces with acceptable quality. Consequently, use of the EarthVision software for representing joints in the 3D geologic framework model as part of database development is not recommended at this time. However, the EarthVision software will still be used for representing variability of rock and joint properties. In FY96, data collection for the rock properties identified in this report will be initiated.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Only "synthetic data" were utilized in this database development progress report.

SOFTWARE QUALITY ASSURANCE: The EarthVision software (Version 2.9 Beta) was used in this report. This software is commercially available. However, the CNWRA does not have access to the source code; therefore, it is not controlled under the CNWRA Software Configuration Procedures.

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EXECUTIVE SUMMARY

The ongoing Rock Mechanics Research Project under the Repository Design, Construction, and Operations (RDCO) Program Element of the Center for Nuclear Waste Regulatory Analyses (CNWRA) is developing an understanding of the critical parameters associated with Key Technical Uncertainties (KTUs) that are related to prediction of thermal-mechanical (TM) effects on emplacement drift stability and thermal-mechanical-hydrological (TMH) effects on the host rock surrounding the engineered barrier system. After the critical parameters have been identified, realistic near-field rock mechanics analyses using site-specific data will be required to bound or quantify the effects of these parameters in the context of the Yucca Mountain (YM) site so that the Nuclear Regulatory Commission (NRC) staff can review the U.S. Department of Energy (DOE) license application in a timely manner. In this context, a rock mechanics properties database is needed to facilitate analyses and modeling related to rock mechanics and TMH coupling.

The approach adopted for developing the rock mechanics properties database is to build a submodel(s) in the three-dimensional (3D) geological framework model for YM, Nevada, which has been developed by the Geology and Geophysics Element of the CNWRA. This 3D geological framework model is to be used by NRC staff during both prelicensing and licensing phases to assess geological models produced by the DOE and its contractors for analysis of site suitability, design considerations, and repository performance. Three steps have been proposed for the construction of a rock mechanics submodel(s) of the 3D framework model: (i) identify actual data needs for rock mechanics-related activities, (ii) identify the source and obtain the data, and (iii) develop the submodel(s). The activity in FY95 focuses on the first step and assessing the capability of the current 3D geological framework model for representing joints, other rock mechanics property data, and tunnels.

Rock mechanics properties identified in this report are categorized in terms of intact rock properties, joint properties including joint geometry related properties, rock thermal properties, hydrological properties, and parameter properties for rock mass classifications using the Rock Mass Rating (RMR) and the Norwegian Geotechnical Institute (NGI) Tunnelling Quality Index, Q, systems. Some of the parameters identified in the report are derived quantities and may not be directly available. Consequently, relevant test results will need to be collected and processed for generating these parameters.

Modeling material properties (e.g., uniaxial compressive strength) is found to be straightforward. The property values can be added to different lithostratigraphic units in the 3D geological framework model. If sufficient spatial data are available, a 3D submodel with the rock property data can then be built using the methods available in the EarthVision software. This approach has been used successfully at the CNWRA to include porosity and saturated hydraulic conductivity properties for characterizing hydrostratigraphic units in a 3D block model. In FY96, gathering of the rock mechanics properties identified in this report and constructing corresponding submodels for the 3D geological framework model will begin.

None of the four methods evaluated in this study can be used without considerable difficulty in incorporating and representing joints in the 3D geological framework model using the EarthVision software. It is recommended that no further effort be made to use the present version of EarthVision as a tool for representing joints in the 3D geologic framework model in the context of rock mechanics properties database development at this time.

Incorporation of an underground opening into the 3D geologic framework model is neither quick nor straightforward. Two methods available in the EarthVision software were tested to include a tunnel in the model. The amount of preprocessing necessary before incorporating such features into the model is extensive even for a single tunnel. For multiple intersecting tunnels, this preprocessing is excessive. Moreover, the final quality of the joint network map on the tunnel surfaces was of unacceptable quality. It is recommended not to further pursue the use of EarthVision software as a tool for representing the underground excavations in connection with rock mechanics properties database development.

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1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE

The proposed high-level nuclear waste repository at Yucca Mountain (YM), Nevada, is to be excavated about 350 m beneath the surface in the densely welded and devitrified part of the Topopah Spring (TSw2 unit) member of the Paintbrush tuff. The proposed emplacement horizon is about 225 m above the water table. The YM area is characterized by north to northwest trending mountain ranges composed of volcanic and volcanoclastic strata that dip eastward. The strata are broken into en-echelon fault blocks. The geomechanical conditions at the site are characterized by a highly jointed rock mass with prominent vertical and subvertical faults and joints.

The emplacement of radioactive waste in this geologic medium will cause major perturbations to the medium involving coupled thermal, mechanical, hydrological, and chemical processes. Three Key Technical Uncertainties (KTUs) have been identified that, among others, could pose a high risk of noncompliance with the performance objectives of 10 CFR Part 60. These KTUs are related to the predictions of (i) thermal-mechanical (TM) (including repetitive seismic load) effects on stability of emplacement drifts and the Engineered Barrier System (EBS), (ii) thermal-mechanical-hydrological (TMH) (including repetitive seismic load) effects on the host rock surrounding the engineered barrier system, and (iii) the long-term performance of seals for shafts, ramps, and surface and subsurface boreholes. An extensive effort is being made in the ongoing Rock Mechanics Research Project under the Center for Nuclear Waste Regulatory Analyses (CNWRA), Repository Design, Construction, and Operations (RDCO) Program Element in developing an adequate understanding of the critical parameters associated with these KTUs and an approach to reduce the uncertainty among these parameters. The ultimate goals of the research project are to develop a sound base for evaluating the U.S. Department of Energy (DOE) license application and to provide timely guidance to the DOE.

Upon identifying and understanding the critical parameters of the KTUs, realistic near-field rock mechanics analyses to bound or quantify the effects of these parameters in the context of the YM site will be performed to better prepare the reviewers for the relevant license review. These analyses will require site-specific information (data). It is understood that, at this time, such information for the site is very limited and scattered in various documents. Consequently, gathering of this information for analyses purposes is tedious, difficult, and time-consuming. A rock mechanics properties database would facilitate the rock mechanics and TMH coupling related analyses and modeling, especially when the DOE is currently conducting site characterization activities and the gathering data is gradually becoming available.

The Geology and Geophysics Element of the CNWRA is developing a three-dimensional (3D) geological framework model for YM, Nevada. The objective of this geological framework model is to provide the basic geological framework within which variations in geological parameters and features both in and adjacent to the potential repository area can be viewed and analyzed, submodels can be constructed, and alternative models can be considered. This 3D geological framework model will be used by the Nuclear Regulatory Commission (NRC) staff during both prelicensing and licensing phases to evaluate the geological models produced by the DOE and its contractors for analysis of site suitability, design considerations, and repository performance. The 3D model will be used in areas related to regional faulting, seismicity, volcanism, and regional hydrology to address several KTUs. To broaden the utility of this 3D framework model for use in near-field rock mechanical analyses, a submodel(s) that incorporates rock mechanical and hydrological properties needs to be constructed.

The rock properties database is envisioned to have the following characteristics. The database should include the TM units along with the faults and major joints mapped within the model boundaries. Different material properties, measured from the cores recovered from different boreholes within the model boundaries, will be incorporated in the model. The value of a particular property at a given location at which no measurement is available may be estimated from nearby known locations through some interpolation technique. The database should be able to create multiple underground excavations when needed. It should be possible to visualize the joint pattern and distribution of any required material property along the length of each excavation at any specified cross section or a 3D block. Provision should also exist to export necessary information regarding the joint and material properties along any section through the model or any given 3D block for further analyses.

Three steps have been proposed for the construction of a rock mechanics submodel(s) within the 3D framework model. The first step is to identify actual data needs for rock mechanics related activities. The second step is to identify the source and gather the data, and the third step is to develop the submodel(s).

1.2 SCOPE

The focus of rock mechanics properties development in FY95 is to complete the first step. The specific activities include:

- Identification of rock mechanics properties and geological information necessary for evaluating emplacement drift stability and retrievability. The identification of data needs is guided by consideration of potential methodologies and tools to be used for the evaluation.

- Identification of hydrological properties that are important for analysis of coupled effects on repository design and performance. These needs are categorized in terms of objectives of the analyses, methodologies, and tools to be used for the analyses.

- Assessment of the capability of the current 3D geological framework model for constructing a submodel(s) to include the data identified in the previous two items.

2 ROCK MECHANICS AND HYDROLOGICAL PROPERTIES

The rock mechanics and hydrological properties needed to facilitate near-field rock mechanics and TMH coupled analyses and modeling may be divided into two major groups: intact rock properties and joint-related properties. Another important group of parameters is related to rock mass classifications, mainly for the Rock Mass Rating (RMR) (Bieniawski, 1974; 1976) and the Norwegian Geotechnical Institute (NGI) Tunnelling Quality Index, Q, systems (Barton et al., 1974). These parameters will be used in review of the DOE ground support design for the Exploratory Studies Facilities (ESF) and underground facility. The properties associated with these three groups are presented in the following sections along with a separate section for the hydrological properties. It is recognized that rock mass properties are sometimes necessary for near-field rock mechanics and TMH coupled analyses, depending upon the intended objectives. These rock mass properties are not proposed to be included in the database because they can be derived or calculated based on various available empirical equations using the relevant parameter values listed in this database.

2.1 INTACT ROCK PROPERTIES

Since the focus for the development of rock mechanics database is to provide information necessary for numerical simulation of underground structures, the properties needed for intact rock are presented in terms of constitutive laws that conceptually represent the material behavior. Several basic constitutive laws are commonly included in most (both finite and discrete element) numerical codes. They include elastic, Mohr-Coulomb plasticity, Drucker-Prager plasticity, Hoek and Brown, and ubiquitous joint models. The data required for the Hoek and Brown failure model are not discussed here because the Hoek and Brown model deals with rock mass behavior. Therefore, the data required are likely to represent an entire or a large portion of a rock unit. Consequently, they do not need to be incorporated into the 3D geological framework model.

2.1.1 Rock Properties for Elastic Model

The elastic model describes the simplest form of material behavior and is valid for homogeneous, isotropic, and continuous material. The stress and strain relation follows Hooke's law. The fundamental properties required for this model are:

- Unit weight, γ, or mass density, ρ
- Young's modulus, E
- Poisson's ratio, ν

Alternatively, E and ν may be replaced by shear modulus (G) and bulk modulus (K).

Ordinarily, the elastic model is used for a preliminary analysis so that a basic understanding can be obtained. The resultant understanding will then help determine the amount of detail for subsequent analysis to solve the problem. Normally, one of the first requirements is to evaluate the potential for yielding or failure due to concentration of stresses. To perform such an evaluation, additional material models are needed, for example, Mohr-Coulomb plasticity, Drucker-Prager plasticity, Hoek and Brown, and ubiquitous joint models. Specific data needed for the Mohr-Coulomb plasticity, Drucker-Prager plasticity, and ubiquitous joint models are presented in the following subsections.

2.1.2 Properties for Mohr-Coulomb Model

The Mohr-Coulomb model is most commonly used to determine the plasticity of geomaterials. Material properties included in the Mohr-Coulomb yield criterion for describing the shear yielding are:

- Friction angle, ϕ
- Cohesion, c

For describing yielding caused by tension, a tension limit or strength (T) is necessary. After the yield criterion is reached, plastic flow is assumed to occur.

If a nonassociated shear flow rule is considered, then an additional material property, dilation angle (ψ), is required. It should be noted that the Mohr-Coulomb criterion includes only the major and minor principal stresses in the formulation; the intermediate principal stress is assumed to have no effect.

2.1.3 Properties for Drucker-Prager Model

The Drucker-Prager model is suited for 3D stress analysis since all three principal stresses are considered to have an effect on material yielding. This model is used occasionally for two-dimensional stress analysis. The Drucker-Prager yield function contains two material constants:

- Frictional component of the shear resistance, α
- Cohesive component of the shear resistance, κ

Usually, the Drucker-Prager yield function is either adjusted to coincide with the outer apices of the Mohr-Coulomb hexagon, or is inscribed tangentially inside the hexagon (inner bound surface). In either case, material properties α and κ can be calculated from the cohesion, c, and friction angle, ϕ. Similar to the Mohr-Coulomb model, if a nonassociated flow rule is used, then an additional material property, dilation angle (ψ), is required. Also the same as that for the Mohr-Coulomb model, yielding caused by tension is governed by a tension limit/strength.

For either the Mohr-Coulomb or Drucker-Prager yield functions, the yield surfaces can harden or soften according to certain hardening/softening rules based on the variation of the cohesion, friction, and dilatancy with plastic strain through the use of hardening parameters that record some measure of accumulated plastic strain. The number of hardening/softening parameters used depends on the hardening/softening rules selected and is usually material specific. These hardening/softening rules and parameters need to be determined through specific testing programs and constitutive model studies. They will not be included as basic material properties for the 3D framework model of YM at this stage.

2.1.4 Properties for Ubiquitous Joint Model

The ubiquitous joint model is an anisotropic plasticity material model. This model assumes that a solid is made of an assemblage of thin elements bounded by parallel weak planes. The behavior of the interfaces between two neighboring elements may be governed by various yielding criteria. The most commonly used is the Mohr-Coulomb model. It is also possible for yielding of the solid to occur. Consequently, material properties for both the interface and solid are necessary, if the complete deformation behavior of a ubiquitous joint solid is to be evaluated. The most common material properties used for the ubiquitous joint model include:

Solid:

- Cohesion, c
- Friction angle, ϕ
- Dilation angle, ψ
- Tension limit, T

Joint/Interface:

- Inclination angle, θ_j
- Cohesion, c_j
- Friction angle, ϕ_j
- Tension limit, T_j

Other properties that may be included in the ubiquitous joint model are joint dilation angle (ψ_j) and joint spacing (S_j).

2.1.5 Rock Thermal Properties

The following thermal properties are needed for thermal analysis:

- Thermal expansion coefficient, β
- Specific heat, C_p
- Thermal conductivity, k_h
- Thermal diffusivity, α_t

The thermal expansion coefficient, β, is needed to calculate thermal expansion. If linear and isothermal conditions are assumed, β is a constant for each lithostratigraphic unit. However, it is possible that β is a function of temperature. Specific heat and thermal conductivity are needed for heat transfer (diffusion) analysis and for coupled temperature-displacement analysis. Usually, there are linear and nonlinear models, the nonlinearity being described by giving conductivity as a function of temperature.

2.2 JOINT PROPERTIES

Joint properties that are of interest include two groups: (i) those that govern the mechanical behavior of a joint, and (ii) those related to geometric aspects of joints. Each group is discussed separately in the following sections.

2.2.1 Joint Mechanical Properties

Joint mechanical properties are important if the behavior of a rock joint is to be simulated explicitly in the numerical analysis. Similar to the intact rock properties, the necessary joint mechanical properties depend on particular joint constitutive models and their numerical interpretations. Joint constitutive models commonly used in numerical analyses include: Mohr-Coulomb, Barton-Bandis, and

Continuously-Yielding. It should be noted that these joint models are capable of simulating unidirectional rock joint shear and joint behavior. They have been found inadequate in modeling rock joint shear and joint behavior under cyclic and dynamic loading conditions (Hsiung et al., 1994). Suitable rock joint models for simulating joint cyclic behavior are being developed[1]. It is not clear if the properties needed for these new models will be available through the DOE site characterization activities. Therefore, they are not discussed here. However, the database will be updated when these properties become available.

2.2.1.1 Mohr-Coulomb Joint Model

The Mohr-Coulomb model is the simplest model for determining the strength of rock joints. The basic properties necessary for the model include:

- Joint cohesion, c_j
- Joint friction angle, ϕ_j
- Joint dilation angle, ψ_j
- Joint tension limit/strength, T_j

Note that these properties are essentially the same as those listed in Section 2.1.4 for the ubiquitous joint model. The joint dilation angle, ψ_j, is used to simulate joint dilation occurring at the onset of plastic sliding. The Mohr-Coulomb model is an elastic, perfectly plastic model. It does not consider the wear of a joint.

In order to adequately model joint deformation, two parameters are needed:

- Joint normal stiffness, K_n
- Joint shear stiffness, K_s

The joint normal stiffness, K_n, and joint shear stiffness, K_s, are assumed to be constant; that is, they are independent of normal stress.

2.2.1.2 Barton-Bandis Joint Model

In contrast to the Mohr-Coulomb model, the Barton-Bandis joint model was proposed to take into consideration the effect of joint surface roughness on joint deformation and strength (Barton et al., 1985). It is a nonlinear joint strength model. Joint parameters in this model include

- Joint roughness coefficient, JRC
- Joint wall compressive strength, JCS
- Residual joint friction angle, ϕ_r
- Joint normal stiffness, K_n
- Joint shear stiffness, K_s

The attrition of joint surface roughness is usually considered through the reduction of JRC in a piecewise linear fashion. Joint dilation in the Barton-Bandis joint model is assumed to be a function of JRC. An empirical equation is available for the joint dilation calculation. Therefore, additional

[1] RDCO Task 2.3 activities. A report discussing model development will soon be available.

information for the joint dilation angle is not required. The Barton-Bandis joint model assumes a constant K_s, while K_n may be a constant, or an exponential or a hyperbolic function of normal stress.

2.2.1.3 Continuously-Yielding Joint Model

The Continuously-Yielding model can simulate progressive damage of a joint surface under shear displacement and displays irreversible nonlinear behavior from the onset of shear loading (ITASCA Consulting Group, Inc., 1993; Cundall and Lemos, 1988). The basic parameters used in this model are:

- Joint normal stiffness, K_n
- Joint shear stiffness, K_s
- Joint initial friction angle, ϕ_{mo}
- Basic joint friction angle, ϕ
- Joint roughness parameter, R

Parameters K_n and K_s could be treated as constants in the Continuously-Yielding model or assumed to be exponential functions of joint normal stress. If they are assumed to be functions of joint normal stress, additional parameters a_n, e_n, a_s, and e_s are needed. These parameters are constant values. The basic joint friction angle, ϕ, may be the same as the residual joint friction angle, ϕ_r.

It is recognized that some of the joint properties, namely K_n, K_s, a_n, e_n, a_s, e_s, and R for the corresponding rock joint models, are derived parameters. Since these values may not be readily available, derivation of these parameters from existing laboratory test results may be necessary.

2.2.2 Joint Geometrical Properties

Joint geometrical properties needed in the database include:

- Number of joint sets, J_n
- Joint spacing, J_s
- Joint dimensions
- Orientations (dip and strike of each joint or joint set)

The number of joint sets is an important parameter in modeling joints in numerical analysis and a basic parameter for the estimation of the NGI Tunnelling Quality Index, Q, proposed by Barton et al. (1974). This system is used by the DOE in the ground support design of the North Ramp (CRWMS M&O, 1994).

Other important data that need to be collected are the geological mapping data along the ESF. These data are essential for developing various realizations of joint distribution of a particular rock unit of interest. These realizations are expected to provide sufficient bounding of the uncertainties associated with the geological mapping data. Each of the realizations will be incorporated into the 3D geological framework model, if determined feasible. These realizations will be used for the emplacement drift stability analysis to evaluate the adequacy of ground support design and assess the potential effect of drift instability on waste packages.

2.3 HYDROLOGICAL PROPERTIES

A number of hydrological properties are needed to numerically simulate the effects of coupled TM and TMH processes at YM. These properties include:

- Matrix permeability, k_m
- Joint permeability, k_j
- Porosity, n
- Water saturations

Equivalent rock mass permeability may be derived from the matrix and joint permeability or measured directly in the field. It is recognized that the joint permeability will need to be generated for each of the realizations discussed in Section 2.2.2. Data for porosity and water saturations will not be collected in the activities associated with the database development. This information is currently incorporated in the 3D geological framework model in a separate activity at the CNWRA.

2.4 PROPERTIES FOR ROCK MASS CLASSIFICATIONS

The DOE uses two rock mass classification methods in the preliminary design of tunnel supporting system, namely RMR classification and NGI Tunnelling Quality Index, Q (Hardy and Bauer, 1989; CRWMS M&O, 1994). To facilitate the design review on the ground support system, it is necessary to include properties related to these two rock mass classification methods in the rock mechanics property database.

The RMR classification was proposed by Bieniawski (1974; 1976). In this method, five basic classification parameters are used to obtain a total rock mass rating (or total rating score for a rock mass). The total rock mass rating is then adjusted for joint orientation. The five basic rating parameters are:

- Uniaxial compressive strength, σ_c (alternatively, point load index)
- Rock Quality Designation, RQD
- Spacing of joints, J_s
- Condition of joints, J_c
- Groundwater condition, W_c

The RQD is defined as the percentage of core recovered in intact pieces of 100 mm or more in length in the total length of a borehole. The condition of joints accounts for the separation or aperture of joints, their continuity, the surface roughness, the wall condition (hard or soft), and the presence of infilling materials in joints. The groundwater condition is determined in terms of the observed rate of flow into the excavation, the ratio of joint water pressure to major principal stress or by some general qualitative observation of groundwater conditions.

The NGI Tunnelling Quality Index was proposed by Barton et al. (1974), in which an index, Q, for the determination of the tunnelling quality of a rock mass is evaluated according to six basic parameters. These parameters are:

- Rock Quality Designation, RQD
- Joint set number, J_n

- Joint roughness number, J_r
- Joint alteration number, J_a
- Stress reduction factor, SRF
- Joint water reduction factor, J_w

The joint roughness number, J_r, accounts for the condition of joint surface and joint wall contacts. The joint alteration number, J_a, accounts for joint filling conditions and the alternation of joints. J_r and J_a represent the roughness and frictional characteristics of the joint walls or filling materials. The SRF is a total stress parameter. It measures the loosening load of an excavation through shear zones and clay-bearing rock, rock stress in competent rock, and squeezing loads in plastic incompetent rocks. The joint water reduction factor, J_w, is a measure of water pressure.

Table 2-1 provides a consolidated list of rock mechanics and hydrological properties to be included in the database. Keep in mind that some properties identified in the previous sections can be used by more than one model. The parameters listed in this table represent the current thinking. If additional needs develop in the future, this list will be updated.

Table 2-1. Rock mechanics properties for database development

Properties	Remark
Intact Rock Properties	
Unit weight of solid, γ, or mass density, ρ	Elastic, Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Young's modulus of solid, E	Elastic, Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Poisson's ratio of solid, ν	Elastic, Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Friction angle of solid, ϕ	Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Cohesion of solid, c	Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Tension limit/uniaxial tensile strength of solid, T	Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Dilation angle of solid, ψ	Mohr-Coulomb, Drucker-Prager, ubiquitous joint
Thermal-Hydrological Properties	
Thermal expansion coefficient of solid, β	TM, TMH analyses

Table 2-1. Rock mechanics properties for database development (Cont'd)

Properties	Remark
Specific heat, C_p	TM, TMH analyses
Thermal conductivity of solid, k_h	TM, TMH analyses
Thermal diffusivity of solid, α_t	TM, TMH analyses
Porosity, n	TMH analyses
Matrix permeability, k_m	TMH analyses
Joint Properties	
Joint inclination angle, θ_j	Ubiquitous joint
Joint cohesion, c_j	Mohr-Coulomb, ubiquitous joint
Joint friction angle, ϕ_j	Mohr-Coulomb, ubiquitous joint
Joint tension limit, T_j	Mohr-Coulomb, Barton-Bandis, Continuously-Yielding, ubiquitous joint
Joint dilation angle, ψ_j	Mohr-Coulomb, ubiquitous joint
Joint roughness coefficient, JRC	Barton-Bandis
Joint wall compressive strength, JCS	Barton-Bandis
Residual/basic joint friction angle, ϕ_r	Barton-Bandis, Continuously-Yielding
Joint initial friction angle, ϕ_{mo}	Continuously-Yielding
Joint roughness parameter, R	Continuously-Yielding
Joint normal stiffness, K_n	Mohr-Coulomb, Barton-Bandis, Continuously-Yielding
Joint shear stiffness, K_s	Mohr-Coulomb, Barton-Bandis, Continuously-Yielding
Normal stress dependent constants for joint normal stiffness, a_n and e_n	Barton-Bandis, Continuously-Yielding
Normal stress dependent constants for joint shear stiffness, a_s and e_s	Continuously-Yielding

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Table 2-1. Rock mechanics properties for database development (Cont'd)

Properties	Remark
Number of joint sets, J_n	NGI Q method
Joint spacing, J_s	Explicit joint modeling, ubiquitous joint, RMR method
Joint dimensions	Explicit joint modeling
Joint orientations	Explicit joint modeling
Joint permeability, k_j	TMH analyses
Properties for Rock Mass Classification	
Uniaxial compressive strength, σ_c	RMR method
Rock Quality Designation, RQD	NGI Q, RMR methods
Condition of joints, J_c	RMR method
Ground water condition, W_c	RMR method
Joint roughness number, J_r	NGI Q method
Joint alteration number, J_a	NGI Q method
Stress reduction factor, SRF	NGI Q method
Joint water reduction factor, J_w	NGI Q method

3 FEASIBILITY ASSESSMENT FOR INCORPORATING ROCK MECHANICS PROPERTIES IN THE 3D GEOLOGICAL FRAMEWORK MODEL

This section focuses on the feasibility evaluation of applying EarthVision software (Version 2.9 Beta), developed by Dynamic Graphics, Inc. (1994a), for representing joints, underground excavations, and rock mechanics property data in the 3D geological framework model. The 3D framework model, previously described by Stirewalt and Henderson (1995), was constructed using field data collected by the DOE and its contractors. Model boundaries, chosen to encompass the potential repository block and faults in and adjacent to it, extend north-south out to about 5 km from the repository block and east-west from Midway Valley to West Ridge.

3.1 REPRESENTATION OF JOINTS

3.1.1 Essential Joint Data

The data required for representing a joint in the 3D geological framework model of YM using tools available with the EarthVision software are: (i) coordinates of the center of a joint surface; (ii) strike and dip of the joint surface; (iii) dip projection length (i.e., length of joint trace along dip direction); and (iv) strike projection length (i.e., length of joint trace along strike). These data are obtained through the generation of joint distribution realizations as discussed in Section 2.2.2.

3.1.2 Modeling Requirements

3.1.2.1 Accommodating Large Numbers of Joints

A cutoff length (size) will be used to limit the number of joints to be included in a realization of joint distribution, which are generated as discussed in Section 2.2.2. The total numbers of joints for each realization are expected to be extremely large. The ability to include this large number of joints in the 3D geological framework model using EarthVision software is essential.

3.1.2.2 Displaying and Downloading Joint Trace Information in Cross Sections

It is desirable that joint traces in any arbitrary 2D cross sections cut through the 3D framework model can be displayed and the related geometric information can be easily exported. The ability to display the joint data in this manner is important to permit further analysis, for example, potential for drift instability. The ability to export joint geometric information in the desired cross section is necessary for input to a stress analysis code (e.g., UDEC or 3DEC). Using this input, the stress analysis code can provide a detailed analysis for assessing drift stability or potential changes of near-field permeabilities resulting from various perturbations.

3.1.2.3 Three-Dimensional Joint Displays and Joint Data Exporting

Joints need to be displayed in a 3D rock mass block, using the EarthVision 3D viewer tool (Dynamic Graphics, Inc., 1994b). These displays may prove useful for 3D analyses of block stability in which the blocks are defined in 3D by the joint surfaces. The displays would also be useful for viewing joint traces on the tunnel walls from a vantage point inside the tunnel. As discussed in Section 3.1.2.2, it is desirable that the joint data within a 3D rock mass block of interest can be easily exported for preparation for detailed rock mechanics and TMH coupled analyses.

3.1.2.4 Minimum Operator and Central Processing Unit Time to Construct Three-Dimensional Models

The time required for an operator to format the joint data so the joint systems can be built and placed in the 3D model (and in 2D cross sections) should be reasonable compared to the total analysis time, or total time available for the project. The central processing unit time required to actually construct the 3D joint model should also be reasonable.

3.1.2.5 Minimum Disk Space Requirements

The amount of disk space required to construct and store the 3D joint model should be reasonable compared to the available hardware capacity so that hardware currently in use at the CNWRA and NRC can be used for the joint model construction.

3.1.3 Approaches Considered

Four approaches were considered for including the joints in the 3D model, and each is discussed in this section. Strengths and weaknesses of each approach are presented.

3.1.3.1 Method 1 — Merged Faces File

The first approach, tested by using a set of six synthetic joint surfaces, was the merged faces file method for including joints in a 3D model. A faces file is a graphics file that is presented in a format that can be displayed in the 3D viewer of the EarthVision software (Dynamic Graphics, Inc., 1994b). Using this faces file, the joints can be modeled as 3D planes or surfaces (i.e., faces). Then the surfaces representing the joints can be merged with the graphics file representing the CNWRA 3D geological framework model.

A faces file is constructed using the essential data provided for the joint surfaces. The center of the joint along with the strike and dip are used to define the joint surface in 3D. Then the data points for the joint surfaces are converted to a 2grd file (i.e., the EarthVision surface file for representing faults and joints) using the EarthVision 2D Trend Gridder (Dynamic Graphics, Inc., 1994b). After conversion to a 2grd file, a faces file is constructed using the EarthVision faces file generation tool (Dynamic Graphics, Inc., 1994b). At the final step, all faces files are merged using the EarthVision Faces file merge tool to construct the joints in the 3D geological framework model.

Figure 3-1 illustrates a sample 3D joint model constructed by this approach using a test case of six joints, modeled using the EarthVision software system merged faces file (Dynamic Graphics, Inc., 1994b). The joints are displayed using the EarthVision 3D Viewer tool (Dynamic Graphics, Inc., 1994b). In the figure, the stratigraphic model has been sliced back to expose the joint surfaces.

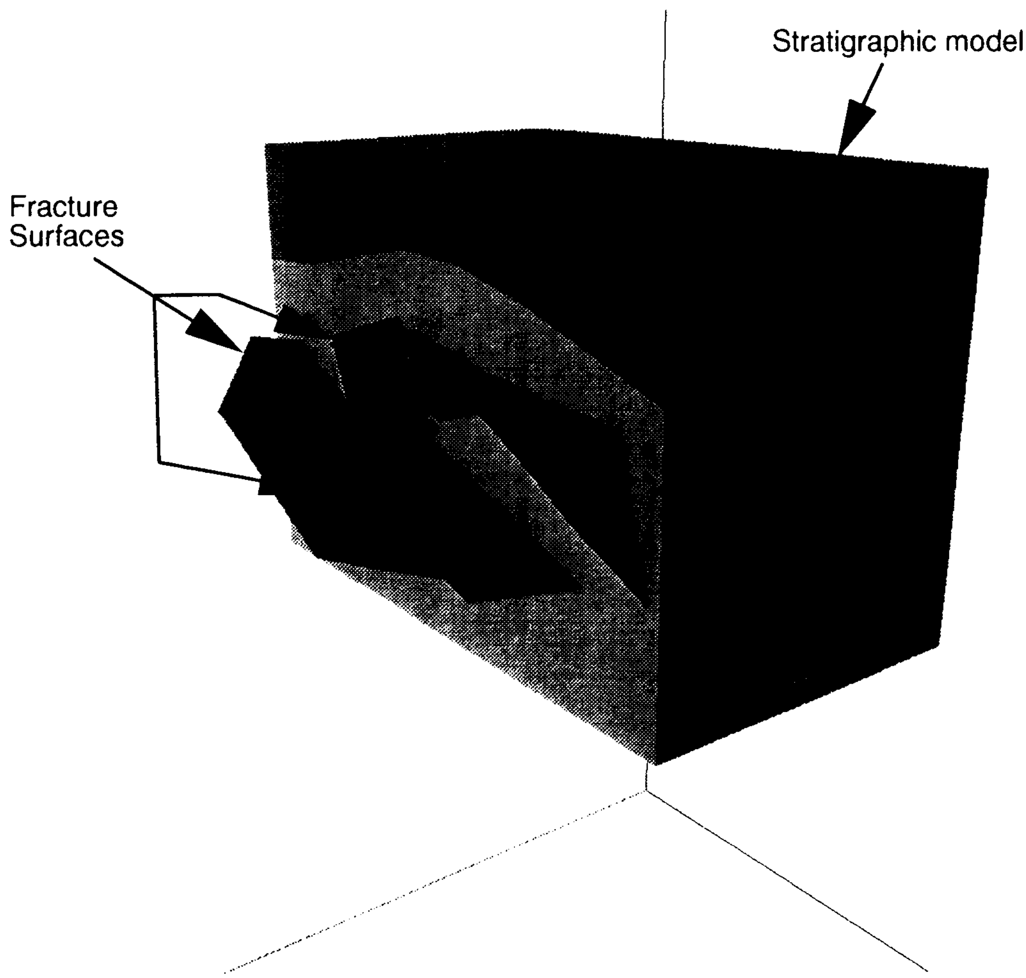

Figure 3-1. Test case joints modeled using the EarthVision software merged faces file method, with display produced using the EarthVision 3D Viewer tool. The lithostratigraphic model has been sliced back to expose the joint surfaces.

The strength of this approach is that the number of joints that can be modeled may be in excess of 1,000[1]. However, a weakness exists because the joints cannot be displayed in randomly chosen cross-section views. When a cross section is created, all zones, blocks, and faults that intersect the cross section are displayed in the cross section view. When the joints are modeled as surface files, they are created and placed into the 3D model as zones with zero thickness so they will not be displayed in cross sections. It also is not possible to view the intersections of the joints with the tunnel walls because the joint surface will extend into the tunnel rather than being terminated at the tunnel wall. Furthermore, the capability does not currently exist in this method to permit processing joint data along a randomly chosen cross section in preparation for exporting it to drift stability and TMH coupled analyses.

Joint traces can be viewed only as intersections with a plane of the 3D model, one of which could be taken to approximate the tunnel wall, if desired. Viewing the joint traces consists of a two-step process—first, cutting the 3D model using the chair-step function of the 3D viewer and then, second, trimming the joints up to the plane of the chair step cut. However, application of this approach would leave the joint surface extending slightly out from the chair-cut plane in the 3D model.

3.1.3.2 Method 2 — Volume Model

This method uses the Geological Structure Builder (GSB) as described in EarthVision Version 2.9 Beta (Dynamic Graphics, Inc., 1994a) to create a 3D volume model. Using this method, the joints would be modeled as small faults within the 3D geological framework model. To create the "fault surfaces" that represent joints, the data provided for the joint surfaces defined in Section 3.1.1 are used, just as was done for Method 1, to construct data files that represent 3D surfaces. These files are then converted into 2grd files, also as for Method 1. Finally, the 2grd files are modeled as faults within the framework model using GSB, which is used to create a sequence file for constructing the 3D volume model.

Figure 3-2 illustrates an example of this approach. The figure shows two representations of joint test cases modeled using EarthVision's GSB (Dynamic Graphics, Inc., 1994a) to produce a volume model. Figure 3-2(a) shows joints displayed in EarthVision's 3D Viewer tool. Figure 3-2(b) illustrates joints represented as lines on a cross section created from the volume model. A strength of this method lies in the fact that it allows viewing the intersections of the joints along the tunnel surface as well as in any slice taken from the 3D model. This method also permits taking cross sections of the 3D model with the joints shown in the cross section. The major weakness of this method is that only approximately 150 joints can be included in the 3D model using the current version of the GSB.[1] Joint geometric information along any cross section may be extracted using this method.

3.1.3.3 Method 3 — pdat 3D Display

A "pdat" file is a property data file that includes the data points that define the 3D surface representing a joint, along with other property fields allowing an outline of the joint plane to be displayed in the EarthVision 3D viewer (Dynamic Graphics, Inc., 1994b). This method is similar to Method 1, but was not tested because it does not provide additional advantages over Method 1. The method also allows more than 1,000 joints to be included[1], as does Method 1. However, only the edges of the joint polygon would be visible rather than the entire joint surface, making it difficult to determine where the joint

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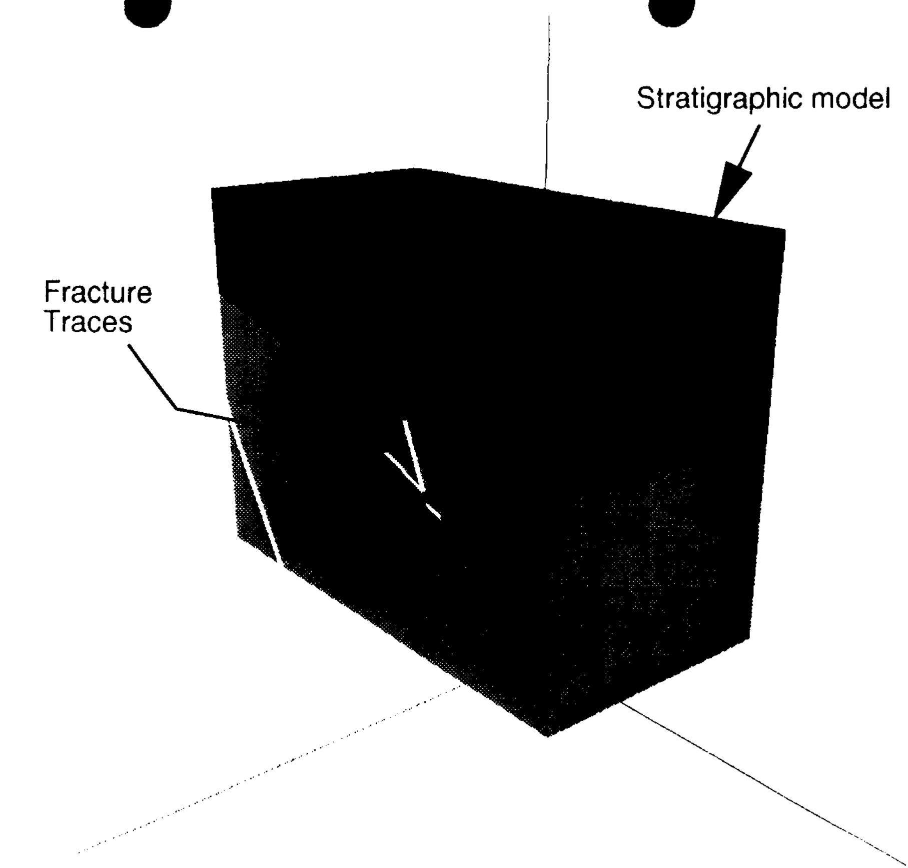
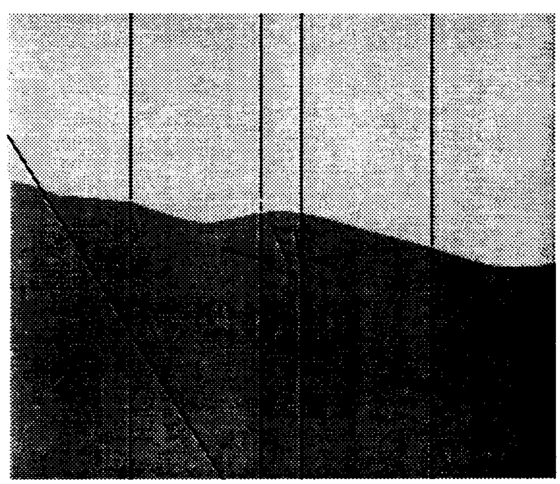
[1] R. Mayoraz, Dynamic Graphics, Inc., personal communication to C. Fenrich, SwRI, June 1995.



(a) Perspective view



(b) Cross section

Figure 3-2. Two representations of test case fractures using the EarthVision software Geological Structure Builder to produce a 3D volume model. (a) Joints as displayed using the EarthVision 3D Viewer tool. (b) Joints represented as intersection lines in a cross section created from the volume model.

intersected any designated slice of the 3D model. Hence, if the joints were modeled using this method, they would not appear on any cross sections taken from the 3D framework model. Extracting joint information for a particular cross sections is not possible using this method or Method 1.

3.1.3.4 Method 4 — Annotation Cross Section Display

An annotation file is a text file that defines to the EarthVision editor those points at which lines, text, and symbols are to be drawn. Using the editor, the annotation file can be saved as a PostScript or plot file, which can be printed or plotted on paper. This method requires that custom software be written to determine the intersection of the 3D joint plane and the cross section plane. Once the intersection has been determined, a line can be drawn on the cross section depicting the intersection of the joint surface with the cross section. Due to time constraints and the fact that this method is similar to Method 2, it was not tested using the hypothetical joint set.

This method allows more than 1,000 joints to be included on any cross section cut from the 3D model. However, it does not display the joints in the 3D viewer tool. Using this method, the joint geometric information would be available only along predetermined cross sections.

3.1.4 Summary

Table 3-1 presents a summary comparison of the four methods discussed in Section 3.1.3, including information on estimated operator hours (based on time to construct 100 joints) and CPU time. Methods 1 and 4 (i.e., merged faces file and annotation displays) combined could be used for representing joints in a 3D model and cross sections in the 3D geological framework model using the EarthVision software. Method 1 provides for including the joints in the 3D model, and Method 4, for representing graphically the joints in cross sections taken from the 3D model. By using these two approaches, over 1,000 joints can be modeled. However, using of the combined methods would require some operator time for formatting the joint data and building the joints. It should also be noted that the joint number of 1,000 used in the discussion in Sections 3.1.3 and 3.1.4 is arbitrary. The actual number of joints is likely to be substantially greater than 1,000, even if a cut-off length (size) is used. Further study will be required to determine if there is a limit for incorporating joints into the 3D geologic framework model.

3.2 TUNNEL MODELING

3.2.1 Approaches Considered

Two different approaches were considered for modeling the repository tunnel. The first approach utilized tools in EarthVision Version 2.9 Beta (Dynamic Graphics, Inc., 1994a). The second approach utilized tools from Dynamic Graphics, Inc. that are not yet commercially released but made available to the CNWRA for this effort.

Table 3-1. Joint modeling method comparisons

Requirement	Method 1 Merged faces file	Method 2 Volume model	Method 3 Property Data Display	Method 4 Annotation Display
Number of joints	1,000+	50–150	1,000+	1,000+
Cross-section display	No	Yes	No	Yes
3D display view joints from outside tunnel	Yes	Yes	Limited, see note 1	No
3D display view joints from inside tunnel	Limited, see note 2	Yes	Limited, see note 3	No
Est. operator time (Hours to build 100 joints)	80 hr	80 hr	40 hr	200 hr to build toolset; 40 hr to build cross sections with 100 faults
Est. CPU time (Hours to build 100 joints)	4 hr	10–12 hr	4 hr	2 hr
Est. disk space (Mb to build 100 joints)	Approximately 10 Mb for joint faces files	Approximately 500 Mb free to generate; approx 100 Mb for final framework model with joints	Approximately 1 Mb	Approximately 1 Mb

Note 1: Joints represented by lines rather than by polygon surfaces. Note 2: Joint surfaces not cut away within tunnel volume, but protrude across tunnel interior. Note 3: Joints represented by lines and may not be visible at tunnel-joint intersections.

3.2.1.1 Tunnel Modeled as 3grd Fault Using EarthVision Version 2.9 Beta

This approach, undertaken at the CNWRA, modeled the tunnel by using digitized map data to produce a footprint of the tunnel, but without tunnel elevations. Using these data along with the slope of the tunnel, the elevation of the tunnel could be determined at each desired location. With these data and by sampling a tunnel data location every 5 m, a property data file was constructed and used to construct a 3grd file. The 3grd file was then used with GSB to generate a fault in the 3D model to mimic the shape of the tunnel. The tunnel is actually represented as a fault block using this approach. This approach allows the material inside the tunnel to be removed. Figure 3-3 illustrates the tunnel generated using this approach.

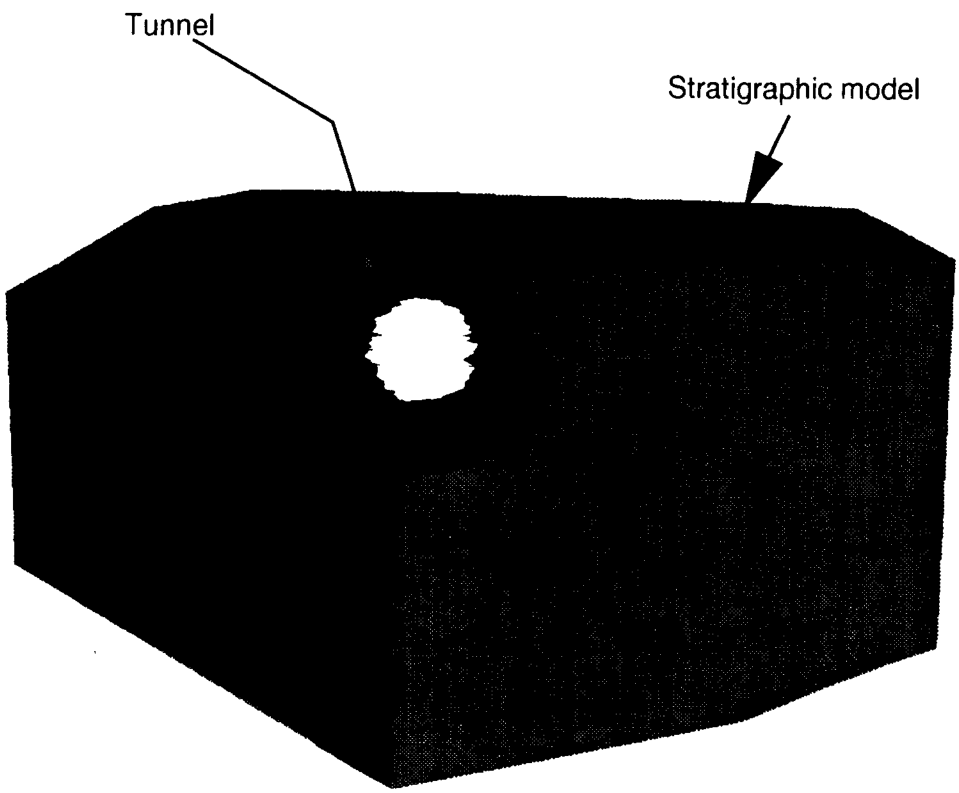


Figure 3-3. The first 1,500 m of the ESF tunnel modeled using EarthVision Version 2.9 Beta. Grid size used to construct the model is 5 m, producing the irregular wall surfaces of the tunnel.

3.2.1.2 Tunnel Modeled as a Zone and Block Using an Unreleased Version of EarthVision

In a test case performed at the request of CNWRA, Dynamic Graphics, Inc. has included the ESF tunnel in the 3D geological framework model of YM. This method modeled the tunnel using polygons creating the tunnel as a separate zone and block, and incorporating it in the 3D model. In this method, the material that is inside the tunnel is what is being modeled, rather than the tunnel surface. The material that lies inside the tunnel is modeled as a separate zone as are the other stratigraphic units. With this approach the tunnel "zone" can be turned off or not displayed in the 3D Viewer to create the tunnel in the 3D model. The software used to accomplish this review is not presently available commercially. The tunnel created by Dynamic Graphics, Inc. did have a smooth surface and was modeled in its total length through the 3D framework model.

Figure 3-4 illustrates a preliminary model of the repository tunnel created by Dynamic Graphics, Inc. using test data supplied by the CNWRA. Dynamic Graphics, Inc. has offered to either model the repository tunnel in more detail as an in-house test case and provide the model to the CNWRA, or to provide the unreleased software to the CNWRA so that modeling could be undertaken. Use of this new and unreleased software is the preferred approach for producing the best representation of underground tunnels in 3D geological framework model. However, the ability of this new approach to include a large number of underground tunnels (drifts) will need to be evaluated. Also, since it is not practical to represent the geometrical properties of joints that intersect tunnels using EarthVision software at the present stage, modeling tunnels alone does not seem to be worth the efforts.

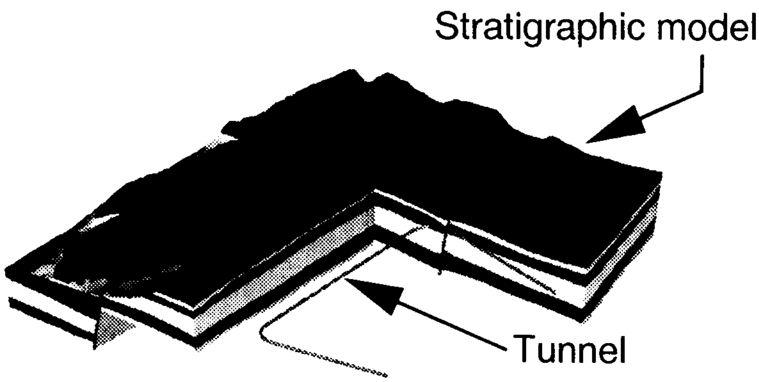
3.3 ROCK PROPERTY MODELING

3.3.1 Cross Sections

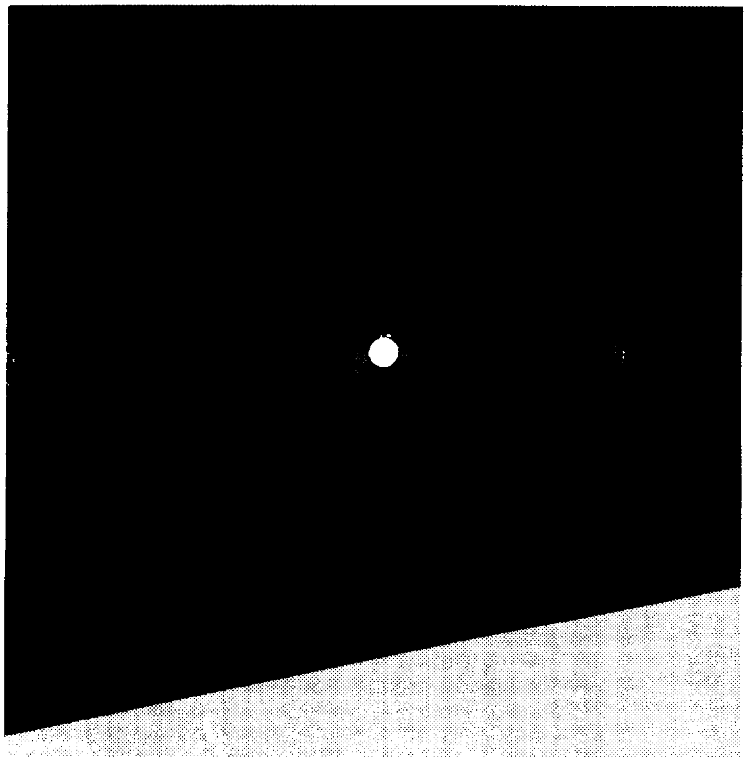
In the CNWRA test case in which the Young's Modulus, Poisson's ratio, and uniaxial compressive strength were included in a cross section, rock property data were provided as hardcopy rather than as electronic files. Thus, the data had to be manually entered into a property data file. The property data file was then used to construct the cross-section annotation files. In the test case, cross sections of the 3D model showing rock property data were constructed by first creating the annotation file displaying only the cross section of the 3D model with no property data. Then, with the aid of a custom program, the rock property data locations and corresponding values were added to the annotation file.

3.3.2 Property Modeling

The rock property data can be included in the 3D model using the GSB. Inclusion of the data is accomplished by adding property values to different lithostratigraphic units in the 3D model. Then using one of the four methods available in the EarthVision Version 2.9 Beta (Dynamic Graphics, Inc., 1994a), along with EarthVision's GSB, a 3D model can be built with the rock property data included in the zone properties of the model. A 3D test case was not performed since insufficient data are available at present for the rock properties. However, a 3D model has been constructed at the CNWRA using porosity and saturated conductivity values, and a similar model can be created when sufficient rock property data are available.



(a) Perspective view



(b) Close up view of tunnel

Figure 3-4. The entire ESF tunnel modeled by Dynamic Graphics, Inc. using an unreleased version of EarthVision. Note the smoothness of the tunnel walls.

4 SUMMARY

Rock mechanical and hydrological properties identified in this report are to be included in the rock mechanics properties database. The identification of data needs is guided by the needs of numerical analyses in evaluating emplacement drift stability and rock fall potentials during the pre- and post-closure periods, and the potential for permeability changes in the rock mass surrounding emplacement drifts due to the effects of mechanical deformation or degradation of rock mass of the heated repository. The identification process is also based on the need for developing a capability for effectively evaluating the adequacy of the DOE ground support design for the underground facility. Some of the parameters identified are derived quantities and may not be obtained directly from DOE site characterization results. In such cases, the relevant test results will be obtained and processed in-house to generate these parameters before they are incorporated into the 3D geological framework model.

Assessment of the feasibility of incorporating rock mechanics properties into the 3D geological framework model using the EarthVision software indicates that modeling of material properties (e.g., uniaxial compressive strength) is relatively straightforward. The data can be incorporated by adding the property values to different lithostratigraphic units in the 3D geological framework model. Then a 3D model with the rock property data included can be built using one of the several methods available in EarthVision, along with its GSB. This approach has been used successfully in the past to include porosity and saturated conductivity properties. In FY96, obtaining rock mechanics properties data identified in Table 2-1 and building of the related submodels for the 3D geological framework model will be initiated.

Representing geometric-related properties (joint and tunnel representations) in the 3D geological framework model, however, is not as straightforward. Four methods were studied. The combination of the merged faces file and annotation cross section display methods could be used if graphical presentation of joints in cross sections is desirable. This approach will require determination of the intersection of the 3D joint plane and the cross section desired before these data can be incorporated into the 3D geological framework model. This approach is prohibitively time-consuming, especially when multiple underground excavations are needed, for example, in the emplacement region. A custom software program will need to be developed for determination of such intersections. Due to the potential magnitude of effort that may be necessary, the use of the present version of EarthVision software for representing joints and underground excavations in the 3D geologic framework model is not recommended at this time.

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