Status on Repository Design - Geotechnical Considerations

Presented to:
Nuclear Waste Technical Review Board

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Outline

- Geotechnical Issues for License Application
- Issue Resolution Strategy
- Current Work Effort
- Summary
Repository Geomechanical Design Issues for License Application

- Thermomechanical properties of lithophysal rocks
  - Thermal conductivity and expansion
  - Strength and deformability (mechanical material behavior)
  - Thermal and mechanical coupling behavior and long-term strength degradation
  - Impact of variability of geologic structure on rock mass properties

- Pre-closure ground support specification

- Post-closure drift degradation and rockfall
Geomechanical Data to Support Design and Performance Assessment

- Existing rock properties and fractures data base (lab and in situ) is extensive for non-lithophysal rocks
- Currently developing (through lab and field testing) expanded data base of:
  - Thermomechanical properties of the lithophysal rocks
    - Importance of porosity-dependence and size effect
  - Evaluation of the geometric properties of joints and lithophysae and their variability
    - Ensuring that our models are based on site-specific geology
  - Time-related degradation effects (static fatigue) on lithophysal and non-lithophysal rocks
- Currently developing postclosure site-specific earthquake ground motions
Rock Properties Estimation and Design Approach

Increasing Confidence, Reduction in Level of Uncertainty
Example of Properties Extrapolation Process Model Calibration - Effects of Lithophysal Porosity on Failure Mechanism and Strength

- Particle Flow Code (PFC) model of uniaxial compression test on middle non-lithophysal rock
- Calibrate stress-strain behavior against lab tests
- Assistance of Itasca Consulting Group - P. Cundall, D. Potyondy, Leads

Simulated Stress-Strain Response

Development of macroscopic shear failure plane

Simulated rock sample, loaded in compression
Model Calibration - Effects of Lithophysal Porosity on Failure Mechanism and Strength - Simulation of Upper Lithophysal Test

![Lab Test Image]

Stress-strain behavior

Ultimate Failure Plane Through Lithophysae

- Stress (MPa)
- Cumulative AE Counts
- Stress (MPa)
- Acoustic Emission

Strain (%)

0 0.1 0.2 0.3 0.4 0.5

0 20 40 60 80

0 100000 120000 140000
Developing Range of Rock Mass Design and Performance Properties - Establishing the Impact of Geologic Variability

- Generate ranges of rock properties from lab, field and numerical extrapolations that account for variability in the rock mass, porosity being the greatest contributor
- Produce variability and confidence limits for properties

**Schematic of the Approach to Incorporating Variability into Design Rock Properties**

- Lab Tests on Large cores
- In Situ Tests

Existing Data - Compressive strength vs porosity all Yucca Mt. Tuffs

Upper Bound All Tuffs

Upper Bound Lith Extrapolation

Lower Bound Lith Extrapolation

Compressive Strength (MPa) vs Effective Porosity (%)
Ongoing Ground Support Evaluation Approach

- Modeling to date indicates support loads and opening deformations expected to be relatively small during pre-closure
  - Time-dependent degradation under thermally-induced loads will need to be accounted for
- Estimated support function in pre-closure period
  - Retain potential raveling rock in lithophysal rock - “membrane”-type support well-suited
  - Support of “keyblocks” and possible surface spalling in jointed non-lithophysal rocks
Ongoing Ground Support Evaluation Approach (Continued)

- Current studies for License Application Design
  - Examining use of various support methods including rock bolts and mesh, steel sets, and shotcrete
  - Longevity of steel support, impact of thin layers of shotcrete on cement carbonation and water chemistry
  - Approach for observation and maintenance of support over pre-closure period
Approach to Post-Closure Rockfall Analysis

- Site-specific ground motions from PSHA
  - Walter Silva, Pacific Engineering; Carl Stepp, Consulting Seismologist; Allin Cornell, Stanford University

- 3D dynamic discontinuum analyses (3DEC) using site-specific joint geometries (non-lithophysal rocks) and site-specific lithophysae distributions (lithophysal rocks)
  - BSC, Itasca Consulting Group, USGS

- Development of probabilistic output of rockfall mass and velocity based on many discrete simulations of varying geologic conditions
Rockfall Assessment Approach

Statistically-based Geologic Input

• Joint geometric parameter variations
• Lithophysae geometry variations
• Rock and joint property variations

3D Dynamic Discontinuum Modeling

Rockfall distribution to Drip Shield Analysis

Ground Motions from PSHA

PGA or PGV

Rockfall (tonnes/KE, etc.)

Mean

PDF at a given g.m. level
Summary

- Major geomechanical issues
  - Preclosure ground support
  - Postclosure seismic stability
  - Increase data base of thermomechanical prop’s, primarily of lithophysal rocks and assess variability across site

- Enhancing confidence
  - Additional laboratory and field testing of lithophysal rocks
  - Incorporation of site-specific geology into numerical model development
  - Continued validation of models against laboratory and field data - use of models for extrapolation of behavior to varying geology
  - Completion of ground support studies - load calculations and longevity estimates
  - Use of true 3D dynamic discontinuum simulations for rockfall estimation
Backup
Laboratory and Field Test Program

- Geotechnical program of detailed geometric documentation of jointing in middle non-lithophysal zone and lithophysae in upper and lower lithophysal zones
- Description of the PFC program used for evaluation of lithophysal rock mechanical constitutive behavior
- Thermal testing in the Lower Lithophysal Unit
Current Laboratory and Field Testing Program on Lithophysyal Rocks

- **Laboratory Testing (Sandia and US Bureau Rec)**
  - Thermal/Mechanical Prop’s of large (12” diameter) core
  - Static Fatigue (time-dependency)
  - Joint Shear Strength
  - All as functions of temperature and saturation

- **Field-Scale Testing in Exploratory Studies Facility and ECRB**
  - Thermal/Mechanical Prop’s (“Slot” flatjack compression)
  - Static Fatigue and thermal degradation by load cycling and long-period loadings
  - Heater testing in lower lithophysyal unit for conductivity measurement
Additional Geotechnical Investigations Now Underway - Joint Geometric Characterization
(Robert Lung, Steven Beason, US Bureau Rec.)

• Study of Joint Geometry for Estimation of Joint Shear Constitutive Behavior and for Rockfall Model Input

• Re-examine joint geometric characteristics, and supplement existing work. Describe statistics of:
  – Dip/dip direction
  – Trace length (continuity)
  – Terminations
  – Rock bridge lengths
  – Non-planarity (large scale roughness)
  – Index properties

• Constitutive Behavior of Rough Joints - Barton-Bandis empirical joint shear constitutive model

Joint geometry showing discontinuous, short trace lengths (shown as T-junctions on painted lines)
Additional Geotechnical Investigations Now Underway - Lithophysae Variability (David Buesch, USGS)

- Geologic investigation of lithophysae in Enhanced Characterization of the Repository Block (ECRB) currently underway
  - Detailed mapping and description of study “panels” along ECRB
  - Linear traverses up ECRB using tape and angular measurements of lithophysal porosity
  - Statistical description of shape, size, porosity, “rim” mineralization, spots, groundmass mineralogy and fracturing
  - Variability of lithophysae will be documented in future AMR
Description of the Particle Flow Code (PFC)

• PFC is a “micromechanical” discontinuum program written by P. Cundall of Itasca Consulting Group

• PFC is selected as it provides the ability to represent the basic physics of deformation and fracture of rock through use of a bonded particle assembly to represent the rock solid matrix, and represents lithophysae as physical voids in the model

• Provides a direct physical analogy to the actual rock - we do not have to make assumptions as to how to include geologic variation - it is done naturally in the model through direct inclusion of structure
Description of the Particle Flow Code (PFC)  
(Continued)

- Particle contact properties (strength, stiffness) are simple in nature and set via calibration against laboratory and/or field testing results. Complex constitutive behavior develops naturally

- Allows detailed study of the deformability and failure mechanisms of the rock, and how this is affected by lithophysae

- Provides simulation tool for extrapolation of thermal and/or mechanical response as function of geologic variation
Is Particle Flow Code in Widespread Use?

- PFC is used extensively worldwide, primarily as a research tool in rock constitutive modeling, rock fracture, granular materials research, powder research, rock dynamics, fluid flow in granular materials, rock cutting, etc.

- Following are some examples in rock mechanics in which program has been used to investigate similar problems to ours:
  - Compaction of porous chalk and acoustic emission in the Ekofisk Oil Field, North Sea
  - Borehole fracturing and breakout in deep wells
  - Mechanisms of shear constitutive behavior of faults and rough joints and comparisons to empirical joint models
  - Time-dependent stress corrosion fracture mechanisms in granite at the URL, Canada
  - Blasting and hydraulically-induced fracturing
  - Oil well stimulation and proppant injection/effectiveness
Description of the Particle Flow Code Program and How it Represents Rock

**Rock Composed of Bonded Particles**

- PFC uses a fully-dynamic, micromechanical discontinuum approach that physically models pores as holes
- Rock modeled as series of bonded particles with shear and normal stress bonds
- Properties very simple - only shear and normal stiffness, tensile and shear strength of contacts, interparticle friction angle after bonded failure
- Non-linearity and complexity of response arises from geometry of particles and porosity
- Allows for determination of propagation of fractures in shear or tension, followed by frictional resistance
- Provides a direct physical analogy to porous rock, and allows direct input of lithophysae variation to model

**Contact Properties**

\[
F_n = k_n U_n \quad \text{Deformability governed by contact stiffnesses}
\]

\[
\Delta F_s = k_s \Delta U_s
\]

\[
F_s \leq \mu F_n
\]
Development of Yield Mechanisms in PFC

- When loaded in compression, bonded assemblies develop non-uniform force chains that induce the formation of axially aligned microcracks.
- These microcracks coalesce into macroscopic fractures.
Model Validation Strategy for Lithophysal Rock

- Due to scale effects, difficult to conduct standard “statistically”-based test program for lithophysal rocks - need to use another approach to bound range of properties

- Validating model(s) (*Particle Flow Code*) that explicitly represent the mechanics of deformation and yield of lithophysal rock

- Validate model directly against lab and field instrumentation data and observations

- Once validated, use model for extrapolation of mechanical behavior and design properties for expected range of lithophysal size, shape and porosity in repository block

\[ PFC 3D \]
\[ Model \]
\[ “Sample” \]

\[ \downarrow \]

Failure Mechanism in Compression

\[ \downarrow \]

Comparison/Calibration of Stress-Strain Response to Lab and Field Results
Thermal Conductivity Testing in the Lower Lithophysal Unit

- Lower lithophysal unit is characterized by voids, or lithophysae, which range in size from centimeters to meters, making a field program an effective method of measuring bulk rock properties.

- Field tests will provide in situ measurements of thermal conductivity (K) and thermal diffusivity (k). Since \( k = \frac{K}{(\rho \cdot C_p)} \), heat capacity (Cp) is also obtained.

- In concert with the field program, a laboratory program is being developed to determine matrix properties of the material and to develop a relationship between thermal conductivity and void volume.
Overview of Field Test Status

- **Test 1**: Single heater and single instrumentation borehole  
  - Status: Completed, preliminary results reviewed in next slide

- **Test 2**: Array of 3 heaters, 3 instrumentation boreholes  
  - Status: In progress

- **Test 3**: Single heater, 2 instrumentation boreholes  
  - Status: In progress
Field Thermal Conductivity Test 1

-Purpose: Initial test; measure thermal conductivity and thermal diffusivity on field scale.

-Test Configuration: Single heater and single instrumentation borehole.

Heater: 5 m long
Thermocouples: In instrumentation borehole. 30 thermocouples cover 5 m.

Testing: Ran heater at low power to remain below boiling; calculated thermal conductivity, thermal diffusivity under partially saturated conditions.

Results: Thermal Conductivity and Thermal Diffusivity versus Time

[Graph showing thermal conductivity and thermal diffusivity over time]