RAI Volume 3, Postclosure Chapter 2.2.1.2.1, Sixth Set, Number 2:

Demonstrate how 20-30 cm block sizes in the UDEC Voronoi model appropriately represent potential yielding surfaces that can organize within a rock mass that has an overstressed zone less than 17 cm thick.

Basis: Yielding of overstressed rock is represented in the UDEC-Voronoi model by movement along block surfaces that form a coherent network oriented parallel to the direction of principal compressive stress (e.g., BSC, 2004, section 7.6.5.1). This modeling approach assumes that sufficient block surfaces exist within the overstressed zone to organize a coherent network of surfaces to appropriately represent yielding within the rock mass. DOE concludes that the overstressed zone in heated drifts is less than 17 cm thick (DOE, 2009, RAI-4), which is spanned by only one to two blocks in the model. By comparison with analyses in, for example, BSC (2004, section 7.6.5.1), widths spanning tens of blocks are need to form a coherent network of surfaces to represent yielding within the compressed sample. By analogy, a 1:10 ratio between block size and width of the overstressed zone can be inferred by ASTM Standard D 7012 (2007). DOE sensitivity analyses only considered block sizes to 10 cm diameter (DOE, 2009, RAI-1), which does not adequately represent the fine-scale discretization shown for coherent yielding in other analyses (e.g., BSC, 2004, section 7.6.5.1).

1. RESPONSE

1.1 INTRODUCTION

The universal distinct element code (UDEC) Voronoi block model sensitivity analyses have considered block sizes down to 10 cm in diameter. The base case analyses have been conducted with block sizes ranging from 20 to 30 cm. As a result of the analyses performed on the 10 cm blocks in response to a previous RAI (see the reference in the Basis for this RAI) and the analyses performed on the 4 cm blocks in this RAI, the 20 to 30 cm block sizes were determined to be appropriate to evaluate the mechanical behavior of the lithophysal tuffs around the drift boundary, taking full consideration that the overstressed zone is less than 17 cm thick.

The ASTM standard identified in the “Basis” statement is not applicable to selection of the block size in analysis of drift stability in the lithophysal rock mass. In the testing of the strength of materials (e.g., concrete) with internal structure (e.g., grains), it is typically recommended (e.g., ASTM D 7012) that the sample size should be at least ten times greater than the average size of the internal structure. The objective of the recommendation is to obtain test results (e.g., material strength) that are independent of the scale of the material internal structure length. If the tests are carried out on smaller samples, the strength is a function of the ratio between the sample size and internal structure size. (The strength presumably reaches an asymptotic value when the ratio is greater than ten.) A coherent fracture pattern forms during the failure when the strength distribution within the sample is relatively homogeneous (i.e., the sample size is much greater than the grain size) and the sample strength is not affected by the grain size. However, the fracture pattern will develop and the sample will fail even if the sample size is comparable to the grain size (or the size of the internal structure). Although a minimum sample size is recommended for testing material strength, in many situations, the size of the overstressed region is of comparable scale to the internal material length scale, resulting in a stronger material response (i.e., yielding at higher stress) than measured in the laboratory. Conservatively, size effect on strength is typically neglected in design of structures, assuming that the material strength is the same as determined in the laboratory test, and is independent of the size of the overstressed region.

Ten blocks across the sample size (or within the overstressed region) in the UDEC Voronoi model are not necessary for a failure mechanism to form. An example of using the Voronoi block model for stability of tunnels in fractured, overstressed rock, in which less than ten blocks occur in a yielded zone, is shown by Hoek and Marinos (2009, Figure 13). In fact, the failure mechanism will form in the UDEC Voronoi block model even if there are only two blocks per sample width. However, the stress at which a sample with two blocks fails would be greater than in the case of the sample with ten blocks per sample width. Because fewer blocks occur per sample width, fewer locations exist where bonds between the blocks can break or fractures can develop. These reductions result in an apparently stronger response of the sample despite the fact that the strengths of the contacts between the blocks are the same. The UDEC Voronoi block model exhibits the size effect very similar to the size effect observed in rock, including lithophysal tuff. In the UDEC drift-stability analyses, the model is calibrated to match the lithophysal rock mass strength estimated from large-diameter tests (BSC 2004, Sections 7.6.4 and E4.1.3.2) and validated with observations of the response of the Exploratory Studies Facility (ESF) and the Enhanced Characterization of the Repository Block (ECRB) Cross Drift under *in situ* stress conditions (BSC 2004, Section 7.6.5.2). To ensure that the size effect in the model is the same in the model as in the lithophysal rock mass, the block size in the model (in the range between 10 cm and 30 cm) (BSC 2004, Section 6.4.1.1) is selected to be approximately the same as the size of the blocks that would form during failure of the lithophysal tuff (see response to RAI 3.2.2.1.2.1-6-001 for details of expected failure mechanisms).

1.2 BLOCK SIZE IN LITHOPHYSAL TUFF

Massive, homogeneous rocks spall in the walls of overstressed excavations. Spalling typically creates thin slabs of rock (sometimes less than 1 cm thick) that detach from the wall. The important feature of these massive rocks is that there is not much size effect on their strength on the length scales greater than the grain size, which is on the order of millimeters. Thus, failure in the massive rocks creates blocks smaller than 1 cm because the strength at the centimeter scale is the same as at the scale of a decimeter or a meter.

However, the analyzed lithophysal rock is not massive. It is a fractured rock mass that also includes varying percentages of lithophysal porosity. The strength of the lithophysal rock mass on the scale of the drift (approximately 5.5 m) is mainly a function of *in situ* fracturing and lithophysal porosity. The results of extensive testing indicate that porosity is a primary factor controlling the strength of the lithophysal rock mass (BSC 2004, Figure E-6). The failure of the lithophysal rock mass is a result of sliding, opening, and extension of existing fractures and propagation of fractures connecting other fractures and the lithophysal voids such as are displayed in maps of lithophysal rocks (Figure A1-20a in BSC 2005 and Figure B-5 in the response to RAI 3.2.2.1.2.1-6-001). Consequently, the failure of the lithophysal rock mass on the drift scale results in broken rock with block sizes on approximately the same scale as the average spacing of fractures and lithophysal cavities.

The small-scale (millimeter-, centimeter-, and decimeter-scale) features in densely welded, crystallized, and lithophysal rocks control the failure mechanisms of the lithophysal rock mass. To understand the conditions of the rock, and the potential for stress-induced failure, the features at different scales are discussed in more detail.

- Millimeter scale – Densely welded, crystallized, lithophysal and nonlithophysal tuff have many similarities at the millimeter scale. The matrix-groundmass is the material between lithophysal cavities, rims, spots, lithic clasts, crystal fragments, and fractures. The originally deposited material, which became the matrix-groundmass, was composed mostly of glass shards and pumice clasts that produce the vitroclastic texture, and as the deposit cooled, the glass crystallized into a groundmass of small grains of feldspar and quartz or cristobalite. Individual grains are typically small (less than 1 mm) and equant in shape (or equigranular), except where (1) crystallization occurred along and perpendicular to grain, glass shard, or pumice clast boundaries, or (2) elongate grains of feldspar formed spherulites. Excluding areas where vapor-phase corrosion has increased the porosity, the matrix-groundmass in the Topopah Spring Tuff lower lithophysal (Tptpll) unit typically has porosity values of about 10.4% (v/v), and rims and spots have porosity values of about 20% to 40% (v/v) (Otto and Buesch 2003). Some of these fine-grained textures and structures are displayed in Figures B-7 and B-10 of the response to RAI 3.2.2.1.2.1-6-001.

- Centimeter scale – At the centimeter scale, lithophysal rocks contain lithophysae, rims, spots, fractures, and matrix-groundmass (e.g., Figures B-6 (a, c, and d) and B-10 in the response to RAI 3.2.2.1.2.1-6-001). At this scale, the matrix-groundmass is ubiquitous and the lithophysae, rims, spots, and fractures form the fabric or structure of the intact rock. Many of these features are associated with lithostratigraphic features such as vapor-phase minerals, rims, borders, and color of adjacent matrix-groundmass that indicate many of the fractures and associated features formed during the period of time when the deposit was cooling; hence, these features are "pre-existing" discontinuities in the rock. Many fractures terminate in rock (and this can include the matrix-groundmass, spots, or rims separately or as a whole), and these terminations form rock bridges; however, some fractures terminate in other fractures or lithophysal cavities. For example, the samples of Tptpll in Figure B-6 (c and d) in the response to RAI 3.2.2.1.2.1-6-001 are from the thermal conductivity test boreholes "Therm-K 005" and "Therm-K 007," which are located about stations 15+30 and 15+41 in the ECRB Cross Drift, and this part of the tunnel has about 12% to 18% lithophysal cavities (Figure A-1 in the response to RAI 3.2.2.1.2.1-6-001 and Figure O-16 in BSC 2004). In these samples, there are numerous small (less than 1 cm long) and closed fractures, many of which terminate at both ends in the matrix-groundmass, and although some truncate into another fracture, the other ends of the fractures are in the matrix-groundmass. Only one fracture in sample Therm-K 007 transects most of the width of the core. Despite the fractures at the centimeter scale of crystallized lithophysal and nonlithophysal rocks, as shown in samples of core depicted in photographs (Figures B-6, B-7, and B-10 in the response to RAI 3.2.2.1.2.1-6-001) and summarized graphs (Figures B8 and B-9 in the response to RAI 3.2.2.1.2.1-6-001), all samples are of good quality and did not disaggregate during drilling or handling. At the centimeter scale, lithophysae, rims, spots, fractures and matrix-groundmass form a series of discontinuities and rock bridges that represent the fabric or structure of the intact tuff rock.

- Decimeter to meter scale – At the decimeter to meter scale, the size, shape, abundance, and spatial (distance between and orientation) distributions of features such as lithophysae (and in part rims and spots) and fractures form the fabric and structure of the lithophysal rock mass. For example, Figure 1 shows a piece of core taken from the lower lithophysal zone in the ECRB Cross Drift. Due to uneven drying of the rock matrix and fractures, the damp fractures and lithophysal holes appear darker in the photograph. Knowing that the sample diameter is 12 inches, the block sizes outlined by the fractures shown in the photograph are approximately 20 cm in diameter.

Source: BSC 2004, Figure 7-1 (a).

NOTE: The core was drilled with water, and the porous rims and fractures (many of which have rims) retain water and appear dark, whereas the matrix-groundmass, which has minimal porosity, dries in a relatively short amount of time.

Figure 1. Lithophysae and Matrix Fractures in the Tptpll in 12-Inch-Diameter Core