RAI Volume 3, Chapter 2.2.1.3.2, Fourth Set, Number 2:

Demonstrate that the dimensions of the tessellated domain in the UDEC-Voronoi model do not affect significantly the calculations of rockfall volume from seismic events.

Basis: The upper boundary of the tessellated domain in UDEC-Voronoi model is set 10.25 m above the initial drift roof (BSC, 2004, Figure 6-116). However, contours of block displacement magnitude intersect the upper boundary of the tessellated domain, indicating that some additional displacement occurs outside this domain (e.g., BSC, 2004, Figure 6-176). Also, plots of the final position of the Voronoi blocks after an analysis (e.g., BSC, 2004; Figures P-17, P-18, and P-24) indicate blocks at the top of the model could be predicted to separate from the overlying elastic domain, which would suggest the caved zone might have extended higher if the model upper boundary had been higher. DOE does not provide a technical basis for the selecting the dimensions of the tessellated domain, and does not provide sensitivity analyses in BSC (2004, section 6.4.2.1) to demonstrate that uncertainty in the dimensions of the tessellated domain do not affect significantly the calculations of rockfall volume during seismic events.

1. RESPONSE

Analyses of emplacement drift stability in the lithophysal rock mass during strong seismic ground motions were carried out in a UDEC Voronoi model in which the region of the rock mass around the drift was represented as an assembly of Voronoi blocks (i.e., the domain was tessellated into Voronoi blocks). This region extends 4.25 m from the drift walls laterally and 10.25 m above the drift crown (BSC 2004, Figure 6-116). The remainder of the model, outside the tessellated domain, was considered to deform elastically. Thus, the model assumption was that inelastic deformation of the lithophysal rock mass, in particular, large deformation associated with fracturing, damage, and unraveling of rock mass, is contained within the tessellated domain.

The size of the tessellated domain and distance of its boundaries from the drift walls was determined from the preliminary simulations and an estimate of the maximum size of the caved region (or the rockfall volume), which must be completely contained within the tessellated domain. Because the model does not allow the caved region to propagate beyond the boundaries of the tessellated region, the assumed size of the tessellated region was confirmed to be sufficiently large that the caved region does not propagate to the boundaries of the tessellated region.

The perimeter of the caved region is contained within the tessellated region and large displacements and disintegration of the rock mass associated with collapse of the emplacement drift do not propagate to the boundaries of the tessellated region (e.g., BSC 2004, Figures 6-176 and P-25). In examples of quasi-static drift degradation sensitivity analysis in which the maximum collapse is induced by degrading rock mass strength to zero, an increase in size of the tessellated domain does not affect the rockfall volume or the caved region size. That is, the caved region remains contained within the original tessellated region.

1.1 ROCKFALL VOLUME COMPARED TO SIZE OF TESSELLATED REGION

The configuration of the emplacement drift and displacement contours after drift collapse and shaking by a seismic event[1] with a 10^{-4} probability of annual exceedance is shown in Figure 1. The figure also shows the outline of the region tessellated in the Voronoi blocks. The contours of certain displacement values (e.g., greater than 0.1 m, as shown as the brown region in Figure 1) cross the upper boundary of the tessellated domain, indicating that additional displacement occurs outside this domain. The reasons for deformation outside the tessellated region are the following:

1. The material outside the tessellated domain is elastic, lithophysal rock (Category 1) with a relatively small Young's modulus of 1.9 GPa (BSC 2004, Table E-11), and it deforms in response to deformation and change in stresses as the drift degrades.

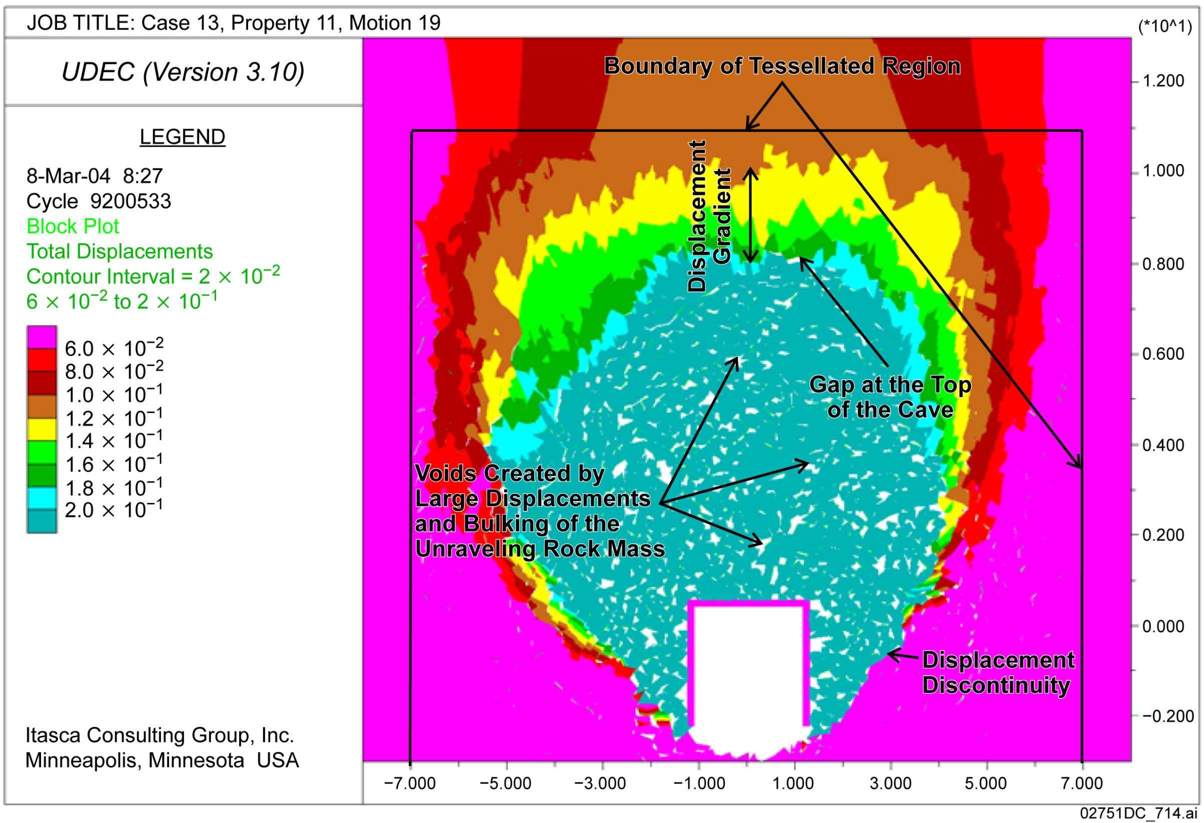
2. The boundary condition on the top of the model, as shown in Figure 6-117 of *Drift Degradation Analysis* (BSC 2004), is the stress boundary condition (equal to the overburden weight). In addition, as can be seen from the same figure and in Figure 6-139 of the analysis (BSC 2004), the height of the model above the drift is relatively small (i.e., 17.5 m above the drift axis). As a consequence, the model generally overestimates deformation and, in particular, bending deformation of the elastic part of the model above the caved region as the emplacement drift degrades. (In the model of a finite size representing infinite half-space, the model boundaries are located at a distance from the excavation where displacements are expected to be small. However, if the stress boundary condition is used on those boundaries, the displacements inside the model will be overestimated because the strength and stiffness of the rock outside the model domain are neglected.)

However, deformation of the elastic overburden (as indicated in Figure 1) does not mean that the caved region expanded to the boundary of the tessellated region, or that the boundary affected the size of the caved region. If a boundary effect were present, gaps would occur along the boundary of the tessellated region. These gaps would be manifested in the displacement contours as displacement discontinuities or regions of large displacement gradients. As shown in Figure 1, the displacement discontinuities and regions of large displacement gradients are

[1] The term "seismic event" in this response generally refers to the ground motion caused by an earthquake. In the context of postclosure seismic consequence analyses, the ground motion is typically characterized by the peak ground velocity (PGV) value of its first horizontal component. For a given value of horizontal PGV, the probabilistic seismic hazard analysis for Yucca Mountain, combined with ground motion conditioning and site-response modeling, gives a mean annual frequency with which the peak velocity value is expected to be exceeded (the bounded hazard curve). Seismic event rates refer, therefore, to ground motion exceedance rates rather than earthquake occurrence rates. For convenience, sets of three-component ground motion time histories are sometimes referred to in terms of their horizontal PGV value (e.g., 0.4 m/s PGV ground motions) or the mean annual frequency of the horizontal PGV value being exceeded (e.g., 10^{-4} ground motions).

completely contained within the tessellated region. Moreover, the displacement field crossing the boundary of the tessellated region is continuous, indicating that near the boundary the tessellated region and the outside elastic domain are mechanically equivalent and deform continuously.

Voids resulting from large block displacements exist in the contour plots and appear as white spaces between the blocks. The voids are consequences of unraveling of rock mass and large displacements that include block rotations. Figure 1 indicates that most of the voids are contained within the region where displacements are 0.2 m or greater and that all of the voids are completely contained within the boundary of the tessellated region. No major voids have been identified in the vicinity of the boundary of the tessellated region.

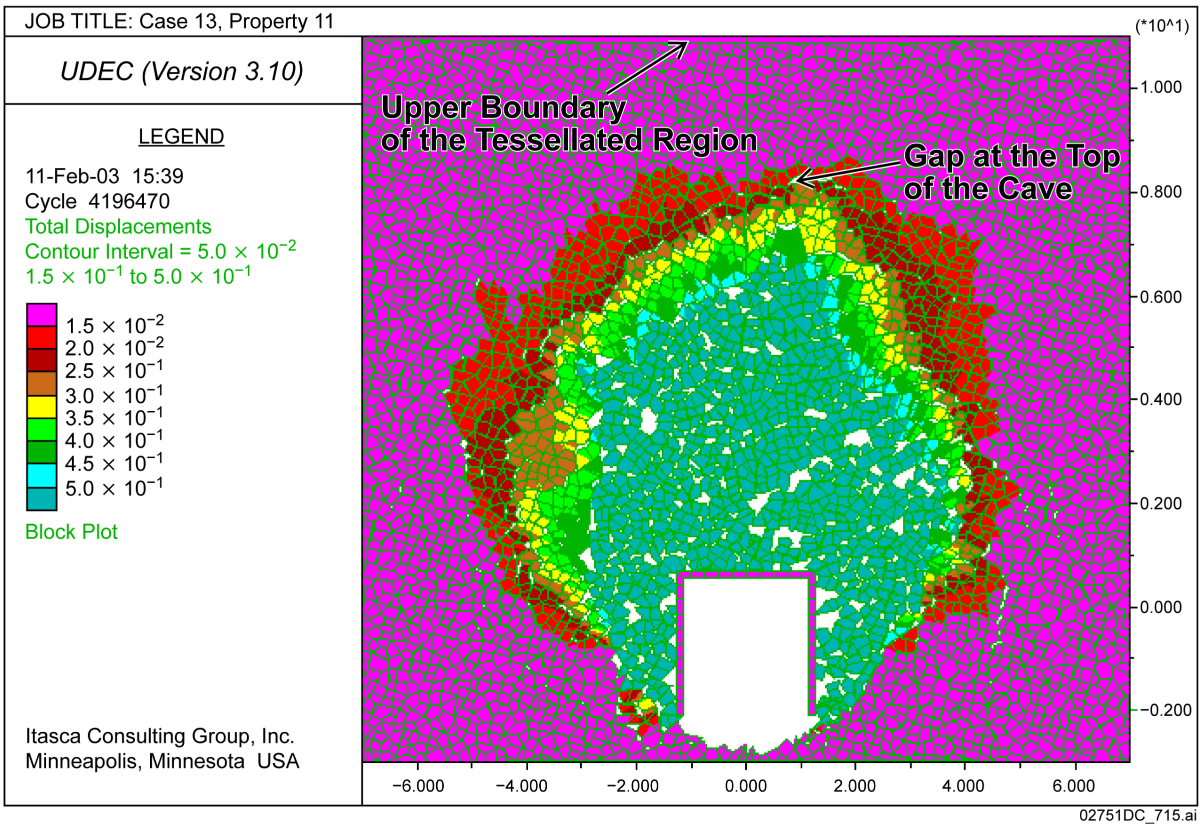


Source: BSC 2004, Figure 6-176.

NOTE: The y-coordinate of the top of the tessellated domain is 11 m; horizontally, the tessellated domain extends between −7 m and 7 m. Displacement contours in this figure quantify the displacement between a particle's initial and final position during the simulation.

Figure 1. Contours of Displacement (m) for Previously Collapsed Drift after Subsequent Shaking by Ground Motions with 1×10^{-4} Probability of Annual Recurrence

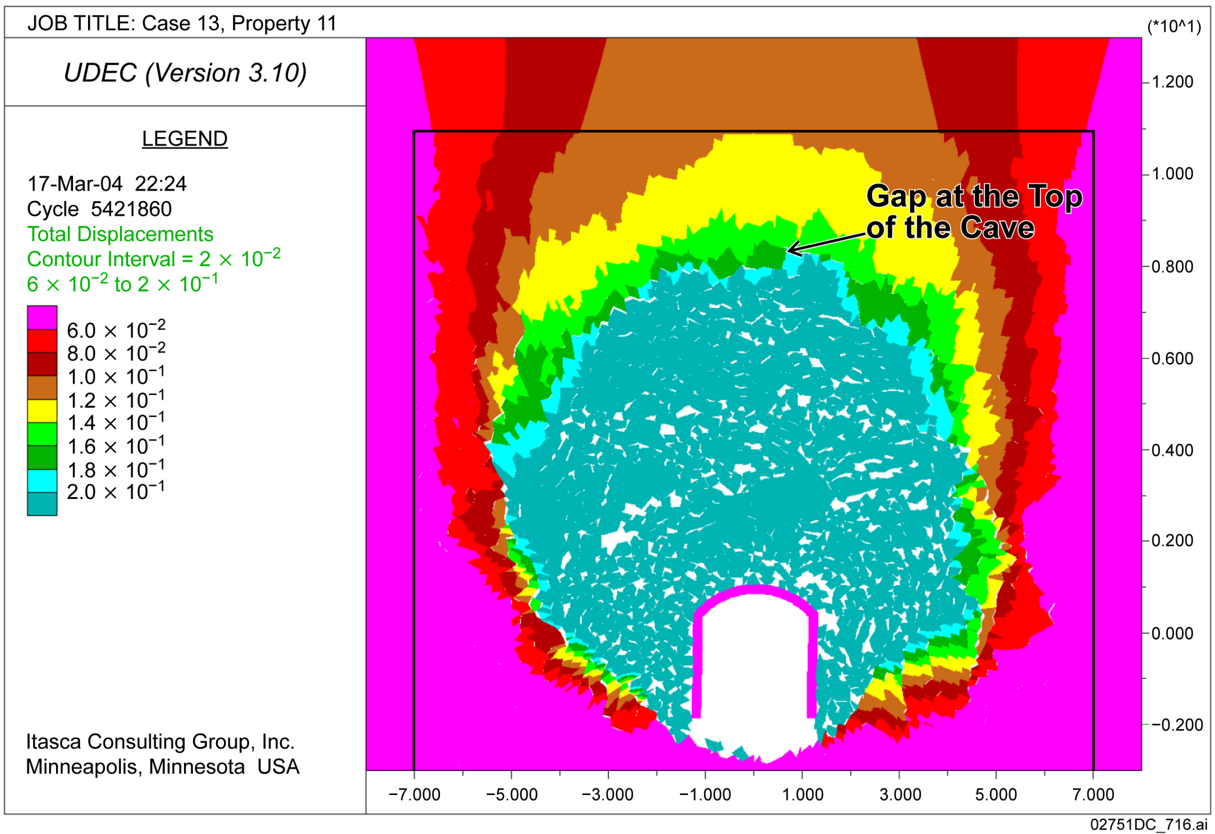
The drift configuration and displacement contours for the case of quasi-static drift degradation for 0.2-m Voronoi block size (response to RAI 3.2.2.1.2.1-6-002) with a rigid, rectangular representation of the drip shield (BSC 2004, Section P2.2.2) are shown in Figure 2. In these calculations, carried out for lithophysal rock mass Category 1, the quasi-static drift collapse is simulated by gradual reduction to zero of the cohesion and tensile strength of the contacts between the blocks. The stress tensor field for the same case is shown in Figure P-17 of *Drift Degradation Analysis* (BSC 2004). The spatial extent of Figure 2 roughly coincides with the tessellated domain. Because the lower bound of displacement contours is set to 0.15 m, the contours of smaller displacements are not differentiated. However, Figure 2 indicates that large displacements of blocks are entirely contained within the tessellated region and that in the vicinity of the boundary of the tessellated domain, the blocks do not undergo the large displacements that would result in formations of voids between the blocks.



NOTE: The y-coordinate of the top of the tessellated domain is 11 m; horizontally, the tessellated domain extends between −7 m and 7 m. Displacement contours in this figure quantify the displacement between a particle's initial and final position during the simulation.

Figure 2. Displacement Contours (m) for Quasi-Static Drift Degradation, 0.2-m Average Block Size

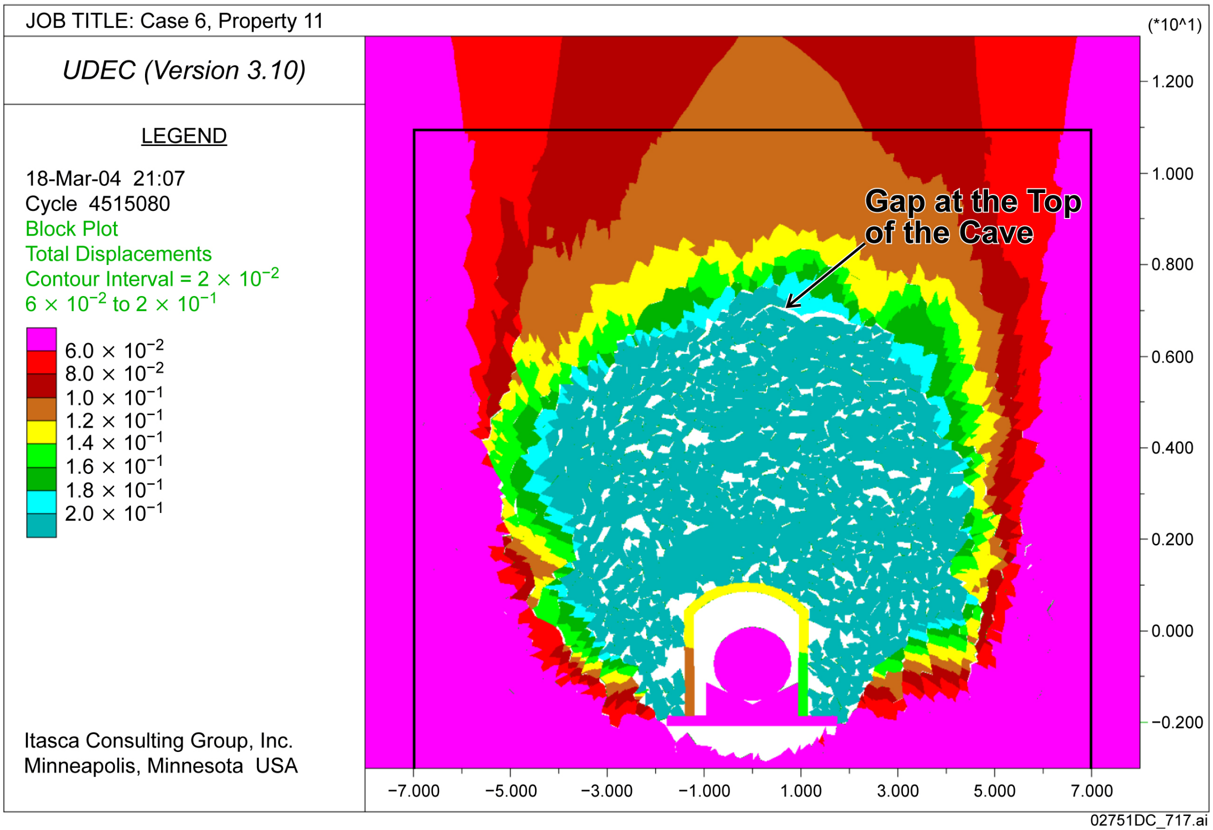
The displacement contour plots for two models with configurations and stress tensor plots shown in Figures P-18 and P-24 of *Drift Degradation Analysis* (BSC 2004) are shown in Figures 3 and 4, respectively. The figures also include the outline of the tessellated domain. The displacement fields are continuous across the boundary of the tessellated domain, and block separation from the boundary is not indicated. The voids created by unraveling of the rock mass are completely contained within the tessellated domain. The indicated gap at the top of the caved region is well away from the upper boundary of the tessellated domain.



Source BSC 2004, Figure P-19.

NOTE: The black lines indicate the boundary of the tessellated region. The y-coordinate of the top of the tessellated domain is 11 m; horizontally, the tessellated domain extends between −7 m and 7 m. Displacement contours in this figure quantify the displacement between a particle's initial and final position during the simulation.

Figure 3. Quasi-Static Drift Degradation, 0.2-m Average Block Size: Contours of Displacement (m) for Deformable Drip Shield with Arched Top, Pinned Bottom, No Invert



Source: BSC 2004, Figure P-25.

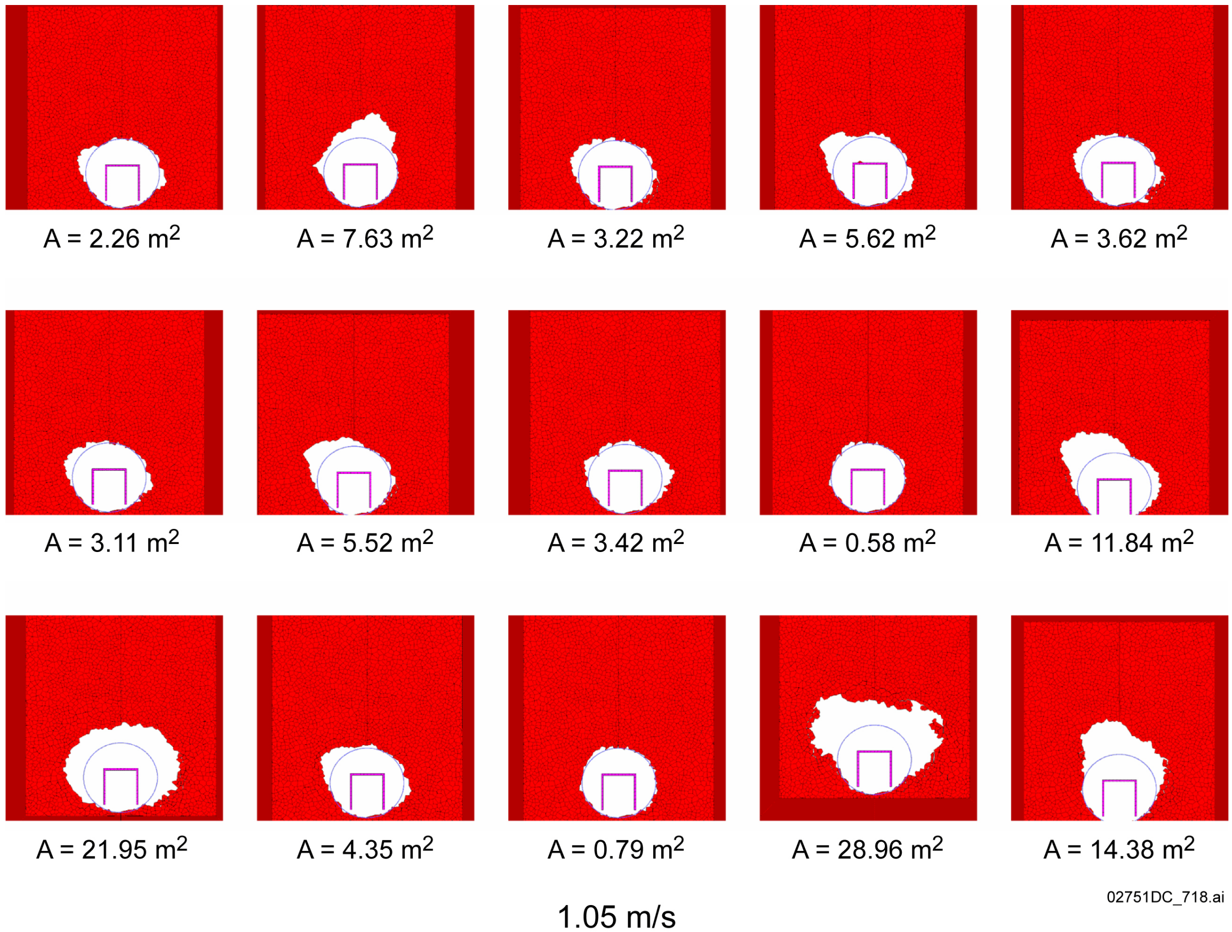
NOTE: The black lines indicate the boundary of the tessellated region. The y-coordinate of the top of the tessellated domain is 11 m; horizontally, the tessellated domain extends between −7 m and 7 m. Displacement contours in this figure quantify the displacement between a particle's initial and final position during the simulation.

Figure 4. Quasi-Static Drift Degradation, 0.2-m Average Block Size: Contours of Displacement (m) for Deformable Drip Shield with Arched Top, Bottom Rests on the Invert

1.2 SIZE OF THE CAVED REGION AFTER SEISMIC EVENTS

Seismically induced rockfall and stable drift profiles in the lithophysal units are calculated for the 0.4, 1.05, and 2.44 m/s peak ground velocity (PGV) levels. The details of the calculations and the results are presented in *Mechanical Assessment of Degraded Waste Packages and Drip Shields Subject to Vibratory Ground Motion* (SNL 2007a, Appendix C). At each PGV level, 15 simulations are carried out for different combinations (provided in BSC 2004, Table 6-44) of the ground motion sets and the lithophysal rock mass categories.

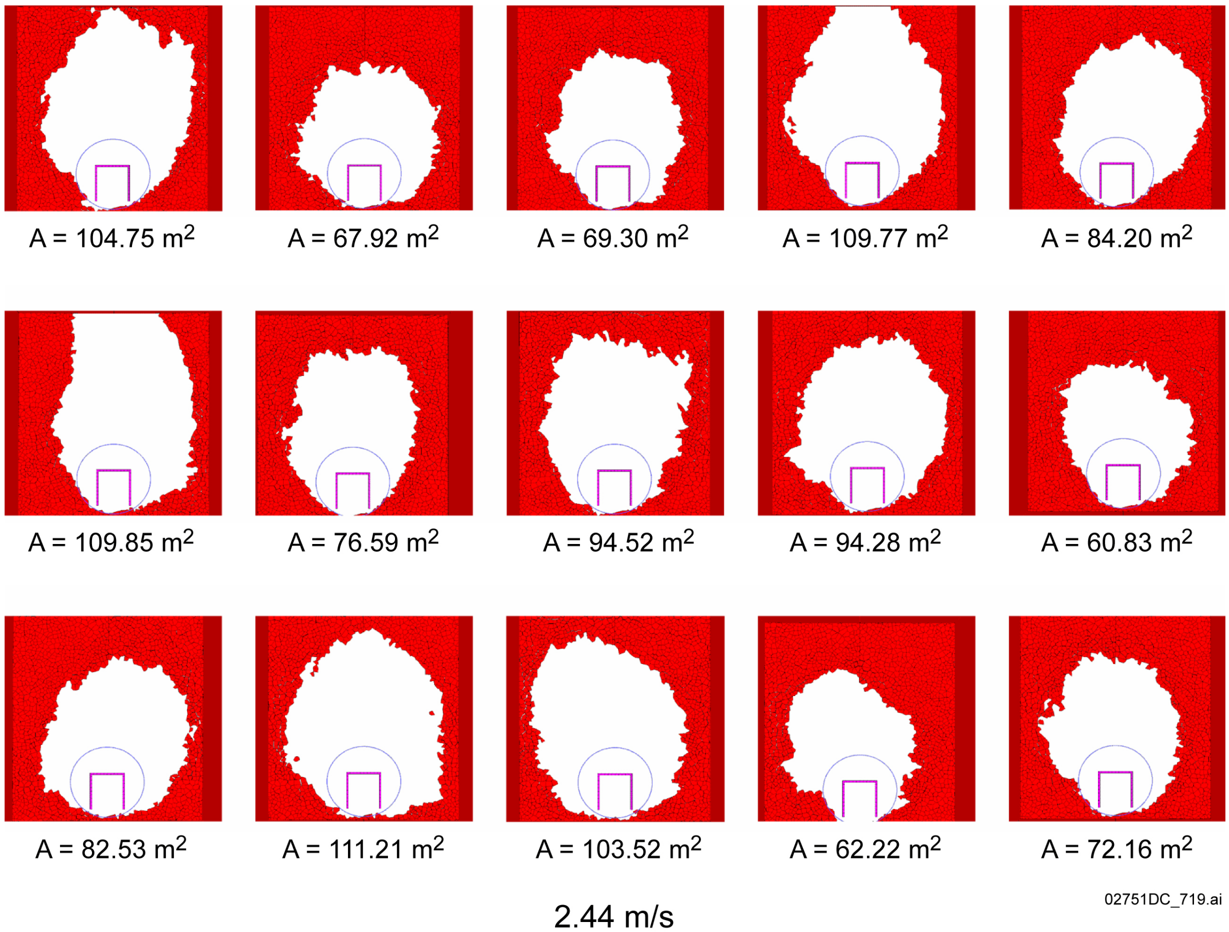
The stable drift profiles for the 1.05 and 2.44 m/s PGV levels are shown in Figures 5 and 6, respectively. The ground motions on the 0.4 m/s PGV level are not shown here, but these rarely cause rock-fall (SNL 2007a, Figure C-1). When rock-fall occurs at the 0.4 m/s PGV level, the amounts are small and only occur in Category 1 lithophysal rock mass, which is such a small fraction of the repository host rock (SNL 2007b, Section 6.7.1.2). The plots show, in red, the part of the model domain with displacement less than 0.1 m relative to the reference point, which is moving as the far field, defined by the incoming seismic ground motions. The threshold of 0.1 m was used irrespective of the rock mass category. However, the results in Section 1.1 show that a 0.1-m threshold results in an overestimate of the caved region in Category 1 rock (e.g., Figure 1). Category 1 rock is the weakest rock category and represents only a small portion of the total rock mass (BSC 2004, *Executive Summary*). It is not expected to comprise the entire perimeter for any single section of emplacement drift. The low stiffness of this category (less than a third of the stiffness of the next stronger rock mass, Category 2 rock) (BSC 2004, Table E-11) results in large displacements (greater than 0.1 m) after drift collapse even in the elastic domain. Consequently, realizations 4 and 6 of Figure 6, which are for Category 1, predict a caved region extending to the upper boundary of the tessellated domain for the 2.44 m/s PGV level. This PGV value is associated with an annual exceedance frequency of 4.52×10^{-7} (SNL 2007b, Section 6.1.7). The combination of a low annual exceedance frequency and the limited amount of Category 1 rock in the repository drifts (about 3%; SNL 2007b, Section 6.7.1.2) indicates that their effect on rockfall volume estimates is not significant. Combinations of the ground motion sets and rock mass categories for different realizations are provided in Table 6-44 in *Drift Degradation Analysis* (BSC 2004). All other realizations show that the caved region is completely contained within the tessellated domain (delineated in lighter red). These realizations demonstrate that the dimensions of the tessellated domain do not affect, and in particular do not limit, predicted rockfall volumes from seismic events.



Source: SNL 2007a, Figure C-2.

NOTES: Realizations 1 to 5 are in the first row realizations 6 to 10 are in the second row, and realizations 11 to 15 are in the third row, all from left to right. The realization numbers correspond to Table 6-44 in *Drift Degradation Analysis* (BSC 2004). The loose blocks that are part of rockfall are not shown. The rectangular shape inside the drift represents the drip shield. The initial drift outline is shown by blue lines.

Figure 5. Stable Drift Profiles and Rockfall Volumes per Unit Length (shown as cross-sectional areas) for 15 Realizations at the 1.05 m/s PGV Level



Source: SNL 2007a, Figure C-3.

NOTES: Realizations 1 through 5 are in the first row, from left to right; realizations 6 through 10 are in the second row, from left to right; and realizations 11 to 15 are in the third row, from left to right. The realization numbers correspond to Table 6-44 in *Drift Degradation Analysis* (BSC 2004). The loose blocks that are part of rockfall are not shown. The rectangular shape inside the drift represents the drip shield. The initial drift outline is shown by blue lines.

Figure 6. Stable Drift Profiles and Rockfall Volumes per Unit Length (shown as cross-sectional areas) for 15 Realizations at the 2.44 m/s PGV Level

1.3 SENSITIVITY ANALYSES

In the analysis of drift degradation during seismic events, the upper boundary of the tessellated domain is 10.25 m above the initial drift roof. However, in the quasi-static analysis of drift degradation (i.e., the cases discussed in Section 1.1), the upper boundary of the tessellated domain is 8.25 m above the drift roof. A back-analysis of the results of the completed calculations demonstrates that the selected size of the tessellated domain does not affect the results of the calculation and, in particular, does not affect the estimated rockfall volume. To further demonstrate the effect of the dimensions of the tessellated domain on the estimates of rockfall volume, a sensitivity analysis is carried out in which the top of the tessellated domain is 13.25 m above the initial drift roof, and the vertical boundaries of the domain are 7.25 m from