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Representation of aleatory uncertainty associated with the seismic ground motion scenario class in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada

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ABSTRACT

The representation of aleatory uncertainty associated with the seismic ground motion scenario class in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, is described. The following topics are considered: (i) occurrence rates for waste package (WP) damage, (ii) conditional distributions for peak ground velocity, (iii) conditional distributions for damaged area on WPs, (iv) distribution of rock fall volume, and (v) probability of WP rupture. Separate results are obtained for commercial spent nuclear fuel and codisposed spent nuclear fuel WPs.

1. Introduction

As indicated in conjunction with Eq. (3.1) of Ref. [1], a large number of probability distributions are used in the 2008 performance assessment (PA) for a proposed repository for high-level radioactive waste at Yucca Mountain (YM), Nevada, to characterize the aleatory uncertainty associated with the occurrence of seismic ground motion events. As described in this paper, representational and computational simplifications can be achieved by coalescing multiple distributions into a single distribution. These representations are used explicitly in the development of the quadrature method for determining expected dose to the reasonably maximally exposed individual (RMEI) from seismic ground motion events over the time interval $[0, 2\times10^4 \text{ yr}]$ as described in Section 4 of Ref. [1]. Specifically, results are presented for (i) occurrence rates for waste package (WP) damage (Section 2), (ii) conditional distributions for peak ground velocity (PGV) (Section 3), (iii) conditional distributions for damaged area on WPs (Section 4), (iv) distribution of rock fall volume (Section 5), and (v) probability of WP rupture (Section 6). Separate results are considered for commercial spent nuclear fuel (CSNF) and codisposed spent nuclear fuel (CDSP) WPs. Distributions for other quantities (e.g., occurrence rates for drip shield (DS) failure) can be determined similarly and are discussed in Sections 7.3.2.6 and 8.3.3.2[a] of Ref. [2].

2. Occurrence rates for WP damage

In the 2008 YM PA, WP damage is characterized as a network of stress-corrosion cracks occurring in the fraction of the WP outer corrosion barrier surface area where residual stresses exceed a threshold value ([3], Section 6.1.5; [4], Sections 6.7.3 and 6.8.5). Damage to WPs can accumulate over a succession of seismic events that damage WPs. In contrast, rupture and puncture are characterized by openings in the WP outer corrosion barrier that permit advective flow, and these outcomes may occur only once ([3], Section 6.9.1).

In the following, occurrence rates for WP damage are derived. The occurrence rates (yr^{-1}) for seismic ground motion events that damage WPs derive from (i) the exceedance frequency $\lambda_G(v)$ (yr^{-1}) for PGV v (i.e., $\lambda_G(v)$ is the seismic ground motion hazard curve) ([3], Section 6.4.3; also, [1], Eq. (3.2)), and (ii) the probability $pD_r(v|\delta_{Ir}, \delta_{Rr}, WT_r, R)$ of nonzero damaged area on a WP of type r ($r=1\sim$CSNF WP and $r=2\sim$CDSP WP) conditional on the occurrence of a seismic ground motion event with PGV v given the existence of conditions defined by the following variables: (a) δ_{Ir}, where $\delta_{Ir}=1\sim$WPs with degraded internals and $\delta_{Ir}=0\sim$WPs with intact internals, (b) δ_{Rr}, where $\delta_{Rr}=1\sim$WPs surrounded by rubble and $\delta_{Rr}=0\sim$WPs not surrounded by rubble, (c) WT_r=outer corrosion barrier thickness (mm) on WP, and (d) R=residual stress

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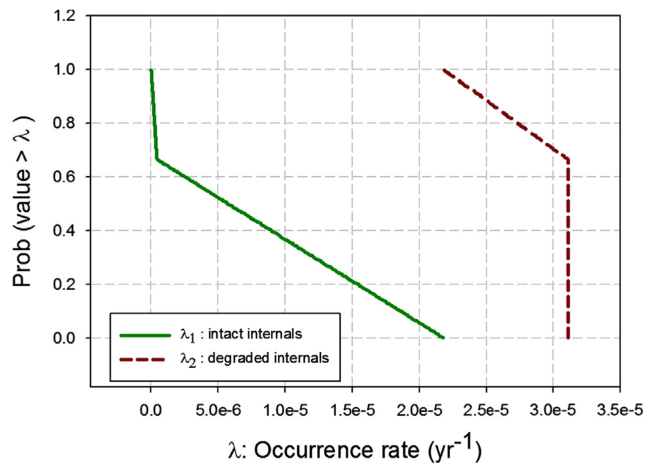

Fig. 1. Estimates for $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ obtained for the sampled values of R=*SCCTHRP* in an LHS of size *nLHS*=300.

failure threshold ([3], Sections 6.5.1.2, 6.5.2.2, 6.6.1.2, 6.6.2.2, 6.9.2, 6.9.3, 6.9.10; also, [1], Eq. (3.5)). For notational convenience in this derivation, the dependence of $pD_r(v|\delta_{Ir}, \delta_{Rr}, WT_r, R)$ on r, δ_{Ir}, δ_{Rr}, WT_r, and R will be suppressed and $pD_r(v|\delta_{Ir}, \delta_{Rr}, WT_r, R)$ will simply be represented by $pWD(v)$.

Given $\lambda_G(v)$ and $pWD(v)$, the occurrence rate λ_D (yr^{-1}) of seismic ground motion events that damage WPs is approximated by

$$\begin{aligned}\lambda_D &\cong \sum_{j=1}^{n} pWD(v_{j-1})[\lambda_G(v_{j-1})-\lambda_G(v_j)]\\ &= \sum_{j=1}^{n}(-1)pWD(v_{j-1})[\lambda_G(v_j)-\lambda_G(v_{j-1})],\end{aligned} \tag{2.1}$$

where $[v_{mn}, v_{mx}]$=[0.219, 4.07 m/s] is the range of values for PGV over which $\lambda_G(v)$ is defined ([1], Fig. 1) and $v_{mn}=v_0<v_1<\ldots<v_n=v_{mx}$. In turn, the representations

$$\begin{aligned}\lambda_D &= \int_{v_{mn}}^{v_{mx}} (-1)\, pWD(v)\, d\lambda_G(v)\\ &= \int_{v_{mn}}^{v_{mx}} (-1)\, pWD(v)[d\lambda_G(v)/dv]\, dv\\ &= \int_{\lambda_G(v_{mn})}^{\lambda_G(v_{mx})} (-1)\, pWD[\lambda_G^{-1}(\lambda)]\, d\lambda\\ &= \int_{\lambda_{mx}}^{\lambda_{mn}} (-1)\, pWD[\lambda_G^{-1}(\lambda)]\, d\lambda\\ &= \int_{\lambda_{mn}}^{\lambda_{mx}} pWD[\lambda_G^{-1}(\lambda)]\, d\lambda\end{aligned} \tag{2.2}$$

result as $\Delta v_j \rightarrow 0$, where (i) the first integral is a Stieltjes integral, (ii) the second integral is the corresponding Riemann integral, (iii) the third integral is the result of a change of variables from an integral on v to an integral on λ, (iv) the fourth integral is a notational change in the limits of integration based on the equalities $\lambda_{mx}=\lambda_G(v_{mn})=4.287\times10^{-4}\,\text{yr}^{-1}$ and $\lambda_{mn}=\lambda_G(v_{mx})=1\times10^{-8}\,\text{yr}^{-1}$, and (v) the fifth and final integral results from an interchange of the upper and lower limits of integration.

The residual stress failure threshold R appearing in $pD_r(v|\delta_{Ir}, \delta_{Rr}, WT_r, R)$ affects the definition of probability distributions that characterize aleatory uncertainty and, in particular, affects the definition of λ_D in Eq. (2.2). However, R is fundamentally a physical property of the WPs. Therefore, given that R is treated as being epistemically uncertain in the 2008 YM PA (i.e., R corresponds to the variable *SCCTHRP* in Appendix B of Ref. [5]), it seems most natural to identify R as an element of $\mathbf{e}_M$ although a case could be made R should be identified as an element of $\mathbf{e}_A$. As a reminder, the 2008 YM PA incorporates the effects of a vector $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$ of epistemically uncertain analysis inputs, where the elements of $\mathbf{e}_A$ are epistemically uncertain quantities involved in the characterization of aleatory uncertainty and the elements of $\mathbf{e}_M$ are epistemically uncertain quantities involved in the modeling of physical processes ([5], Section 3). Computationally, this has no effect on the outcome of the 2008 YM PA because, with either identification, R is an element of the vector $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$ of epistemically uncertain quantities sampled in the LHS indicated in Eq. (11.1) of Ref. [5]. However, in general although not implemented in the 2008 YM PA, the hazard curve $\lambda_G(v)$ is epistemically uncertain (i.e., $\lambda_G(v)$ is an important analysis input that is not known with certainty [6]) and thus is appropriately viewed as an element of $\mathbf{e}_A$. As a result, the rate λ_D defined in Eq. (2.2) is actually a function $\lambda_D(\mathbf{e})$ of epistemically uncertain analysis inputs.

The occurrence rates $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ defined in Eqs. (4.3) and (4.5) of Ref. [1] and appearing in Eqs. (4.7) and (4.8) of Ref. [1] are rates of the form defined in Eq. (2.2). Specifically,

$$\lambda_1(\mathbf{e}) = \int_{\lambda_{mn}}^{\lambda_{mx}} pWD_2[\lambda_G^{-1}(\lambda)|\delta_{I2}=0,\ \delta_{R2}=0,\ WT_2=23\text{ mm},\ R]\, d\lambda \tag{2.3}$$

with (i) $r=2$ indicating CDSP WPs, (ii) $\delta_{I2}=0$ indicating intact internals, (iii) $\delta_{R2}=0$ indicating WPs that are free to move beneath intact DSs, (iv) WT_2=23 mm corresponding to an essentially undiminished outer corrosion barrier, and (v) R and possibly $\lambda_G(v)$ elements of $\mathbf{e}$. Similarly,

$$\lambda_2(\mathbf{e}) = \int_{\lambda_{mn}}^{\lambda_{mx}} pWD_2[\lambda_G^{-1}(\lambda)|\delta_{I2}=1,\ \delta_{R2}=0,\ WT_2=23\text{ mm},\ R]\, d\lambda, \tag{2.4}$$

with (i) r, δ_{R2}, WT_2, R and $\lambda_G(v)$ defined the same as in Eq. (2.3) and (ii) $\delta_{I2}=1$ indicating degraded internals (Fig. 1). When a linear scale is used for the abscissa in Fig. 1, the two CCDFs are piecewise linear with slopes that change at a single point.

The epistemic uncertainty $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ shown in Fig. 1 results from uncertainty in R=*SCCTHRP*, the residual stress threshold for Alloy 22 (see [5], Appendix B). As sampled, *SCCTHRP* is a percent of a base value of 351 MPa and is related to the stress corrosion cracking threshold *SCCTHR* (see [5], Appendix B), by *SCCTHRP*=(*SCCTHR* × 100)/(351 MPa).

The preceding representations for $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ use the final integral representation for λ_D in Eq. (2.2); however, the other integral representations for λ_D in Eq. (2.2) provide equally valid representations for $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$. For example, use of the second integral representation in Eq. (2.2) results in

$$\lambda_1(\mathbf{e}) = \int_{v_{mn}}^{v_{mx}} (-1)pWD_2(v|\delta_{I2}=0,\ \delta_{R2}=0,\ WT_2=23\text{ mm},\ R)\,[d\lambda_G(v)/dv]\, dv \tag{2.5}$$

and

$$\lambda_2(\mathbf{e}) = \int_{v_{mn}}^{v_{mx}} (-1)pWD_2(v|\delta_{I2}=1,\ \delta_{R2}=0,\ WT=23\text{ mm},\ R)\,[d\lambda_G(v)/dv]\, dv, \tag{2.6}$$

which avoids the use of the inverse function $\lambda_G^{-1}(\lambda)$ but requires the determination of the derivative $d\lambda_G(v)/dv$. In many ways, the initial Stieltjes integral in Eq. (2.2) provides the simplest representation for $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$.

The values for $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ in Fig. 1 are computed with the assumption that WT_2=23 mm and represent the occurrence of WP damage as a stationary Poisson processes for the time period [0, 2.0×10^4 yr]. As corrosion thins the outer corrosion barrier, WT_2 slowly decreases, and the corresponding values of $\lambda_1(\mathbf{e})$ and $\lambda_2(\mathbf{e})$ change slowly over time; thus the occurrence of WP damage actually is characterized by non-stationary Poisson processes. However, the amount of WP thinning is negligible for the time