Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

PROBABILISTIC SEISMIC EVALUATION OF REINFORCED CONCRETE TUNNEL LININGS AFFECTED BY ALKALI-SILICA REACTION

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ABSTRACT

Alkali-silica reaction (ASR) has been identified as an age-related degradation mechanism affecting concrete structures, including nuclear power plants in Canada, Japan, France, and the United States. This study proposes a practical approach for probabilistic seismic evaluation of reinforced concrete structures affected by ASR. The proposed approach is based on the Conservative Deterministic Failure Margin (CDFM) method for developing seismic fragilities, outlined in EPRI 3002012994. The CDFM method is adapted for evaluating ASR-affected concrete structural elements by modifying the stress demands in the concrete to account for the volumetric change due to ASR. The philosophy for incorporating ASR into the CDFM method can also be applied to other seismic fragility evaluation methods, for example, the Separation of Variables (SOV) approach (also outlined in EPRI 3002012994). This paper also presents a hypothetical case study using the proposed approach to evaluate a reinforced concrete tunnel lining affected by ASR.

INTRODUCTION

Alkali-silica reaction (ASR) is a chemical reaction between the alkali content in cement paste and reactive silica minerals contained in some types of concrete aggregates. The reaction produces a gel that swells if moisture is present. ASR has been identified as an age-related degradation mechanism affecting concrete structures, including nuclear power plants in Canada, Japan, France, and the United States (EPRI 3002010093 (2017)). This study proposes a practical approach for probabilistic seismic evaluation of reinforced concrete structures affected by ASR in nuclear power plants.

The proposed approach is based on the Seismic Probabilistic Risk Assessment (SPRA) framework as shown in EPRI 3002012994 (2018). SPRA requires the use of seismic fragilities for structures, systems, and components (SSCs). EPRI 3002012994 provides guidance for developing seismic fragilities following two approaches: the Separation of Variables (SOV) approach or a hybrid fragility approach. The SOV fragility approach is more rigorous and resource-intensive; it requires the median values and logarithmic standard deviations of all variables affecting capacity and demand, and is recommended for use for SSCs that dominate the risk profile. The hybrid fragility approach is a simplified approach for developing fragility curves that prioritizes the determination of the High Confidence Low Probability of Failure (HCLPF) seismic capacity. It is based on the Conservative Deterministic Failure Margin (CDFM) method, which is summarized in the next section.

This paper discusses incorporating ASR effect in the CDFM method, since this simplified approach was sufficient to demonstrate meeting the target performance objectives of the case study. The proposed approach can be incorporated in the SOV approach when a probabilistic characterization of the capacity and demand variables is available.

The scope of this study includes the following:

1. A description of the proposed framework for consideration of ASR effects in the CDFM method for seismic fragility outlined in EPRI 3002012994 (2018).
2. An example application of this framework (i.e., case study) in the seismic fragility evaluation of reinforced concrete tunnel linings considered to experience ASR.

PROPOSED APPROACH

Basic CDFM Method

The CDFM method is a deterministic method for estimating ground acceleration capacity to achieve a seismic capacity corresponding to approximately the 1% non-exceedance probability (NEP) for a specified target response spectrum shape. For CDFM's application to SPRA as part of the hybrid fragility approach, the specified target response spectrum is the reference earthquake (RE).

The CDFM method implicitly accounts for the effects of uncertainties by setting defined levels of conservatism to the material properties and analysis methods used to calculate SSC seismic capacity and demand. These levels depend on the type of SSC and the failure mode being investigated. General criteria for introducing conservatism in CDFM capacity and demand are summarized here:

1. Demand: the elastic response of the investigated SSC to the RE is defined at approximately 84% NEP.
2. Capacity: Capacities for ductile failure modes are specified at 98% exceedance probability (EP). For brittle failure modes, this capacity should be reduced to 99% EP.
3. Inelastic energy absorption: for ductile failure modes, inelastic distortion beyond elastic limits is allowed, provided it aligns with a 5% failure probability level. The inelastic energy absorption factor is conservatively estimated at 84% NEP to accommodate this distortion.

Table 3-10 in EPRI 3002012994 (2018) includes a summary of CDFM method criteria for hybrid fragility application in SPRA, including load combination, ground response spectrum, seismic demand, damping, structural model, soil-structure-interaction, material strength, static strength equations, inelastic energy absorption, and in-structure (floor) spectra generation. A detailed explanation and example applications of the CDFM method are presented in EPRI 3002012994 (2018).

Including ASR Effect in the CDFM Method

The effect of ASR on the CDFM method is attributed to its effect on both structural capacities and structural demands.

Historically, the assessment of ASR effects has primarily concentrated on the degradation of material properties, with less focus on how ASR influences structural capacities. Extensive research has investigated and quantified ASR's impact on unconfined material properties, such as tensile strength, elastic modulus, and compressive strength (Giaccio et al. 2008, Jones and Clark 1998). The Institute of Structural Engineers (1992) reported that ASR causes a reduction in these properties in unreinforced concrete, with compressive strength experiencing a modest decline as ASR advances, while elastic modulus and tensile strength show more pronounced reductions. However, in reinforced concrete structures, this reduction in material properties does not necessarily lead to reduced structural capacity, for example, the ASR-induced expansion in concrete is restrained by the steel reinforcement, resulting in tension in reinforcement and compression in concrete, this chemical prestressing effect induced by ASR can counteract the material degradation from concrete.

From a structural demand perspective, the effects of ASR resemble those caused by environmental factors that lead to expansion in concrete, or restrained dimensional changes that induce stress in structural elements. Reinforced concrete members experience ASR-induced loading due to differential expansions within the structure and constraints imposed by boundary conditions. The magnitude and nature of ASR-induced expansion depend on the degree of internal and external restraints. Internal restraints are provided by steel reinforcement, while external restraints are provided by boundary conditions or adjoining structural components.

To include ASR effects in the CDFM method, the following criteria, listed in Table 3-10 in EPRI 3002012994 (2018), can be modified as follows:

- Load combination: the CDFM method uses normal operation load plus the reference earthquake as load combination. As discussed above, ASR induces structural demand due to both internal and external restraints. Therefore, ASR demand should be considered as part of the normal operation load in this framework.
- Material strength and static strength equations: for non-brittle failure modes, the CDFM method uses code-specified minimum strength and code ultimate strength equations or 95% EP actual strength and 84% EP actual strength equations if test data are available. For brittle failure modes, the CDFM method uses 98% EP material strength and 95% EP strength equations. ASR effects on percentage EP material strength and strength equations should be based on test data. However, certain studies (the Institute of Structural Engineers (1992)) found that, for reinforced concrete, ASR does not reduce structural strengths due to the chemical prestressing effect that results from ASR.

CASE STUDY

This section presents a case study of a performance evaluation of a reinforced concrete tunnel lining affected by ASR using the above-proposed approach. The reinforced concrete tunnel lining has an inside diameter of 17 ft and a thickness of 15 in. The tunnel lining is reinforced with Gr. 60 #5 rebars at 12 in. spacing in the longitudinal direction and #5 rebars at 15 in. spacing in the hoop direction with a concrete cover of 3 in.

This case study assumes that ASR does not affect the structural capacity (Institute of Structural Engineers (1992)) of the reinforced concrete tunnel lining. Alternatively, if test data were available, the ASR effect on structural capacity can be evaluated using percentage EP material strength and strength equations presented above and detailed in Table 3-10 in EPRI 3002012994 (2018).

Material Properties

The specified concrete compressive strength is 4,000 psi, and the design steel yield strength is 60,000 psi.

The median material properties are determined following the recommendations in EPRI 3002012994 (2018) and are summarized as follows:

- The median transformation factor for non-ASR affected concrete is 1.5 (median concrete compressive strength can be calculated using design compressive strength multiplied by the median transformation factor). This case study assumes that ASR does not affect the structural capacity of the reinforced concrete tunnel lining. Therefore, this median transformation factor remains applicable.

- Median steel yield strength is 66,000 psi (Table 4-6 in EPRI 3002012994 (2018)).

Reference Earthquake

The reference earthquake (RE) for this case study is a Design Basis Earthquake (DBE) with a horizontal and vertical peak ground acceleration (PGA) of 0.15 g. The horizontal and vertical design spectra from Regulatory Guide 1.60 (2014) are scaled to have a PGA of 0.15g.

Evaluation Acceptance Criteria

The acceptance criteria for this case study are obtained from ASCE/SEI 43-19 (2019) as follows:

1. Equal or smaller than 1% probability of unacceptable performance at the design basis earthquake (DBE) ground motion, and
2. Equal or smaller than 10% probability of unacceptable performance at 1.5 times the DBE ground motion.

As stated above, in this case study the DBE is the RE.

Unacceptable performance refers to different potential failure modes such as compressive crushing, axial-flexure bending failure, shear failure, etc. In this case study, for brevity, only compressive crushing in the circumferential direction of the tunnel lining is evaluated and presented.

Demands

Demands from loads during normal operations of the tunnel lining include rock load, swelling of concrete, and ASR load. These demands are calculated for a rock-quality designation (RQD) of 75%.

Methodologies of analyzing reinforced concrete tunnel linings under rock load and seismic load are well documented in existing literature (for example, in Wang (1993)) and are not the focus of this paper. Therefore, the demands are not explicitly evaluated in this case study. The axial force demands in the circumferential direction of the tunnel lining due to rock load and seismic load (from RE) used in this case study are calculated using methods detailed in Wang (1993). These design equations combined with minimum material properties listed above result in conservative demands from rock load and seismic load, which are considered to align with the target levels of confidence in the CDFM method. The axial force demands from rock load and seismic load are summarized in Table 1.

Demands from ASR load and concrete swelling are calculated using a finite element (FE) model, including the reinforced concrete tunnel lining and surrounding rock, as illustrated in Figure 1. The surrounding rock is modeled as a square block of width and height equal to approximately 10 times the internal diameter of the concrete section. Rock dimensions are much greater than the dimensions of the concrete lining so that the stress field at the location of the concrete member is unaffected by the rock boundary.

The concrete is modeled with 4-node plane strain elements with a thickness of 1 in. Concrete section elements have an average size of 3 in. by 3 in. and are defined with linear elastic concrete material properties listed in the “Material Properties” Section. Material non-linearity of concrete is not considered for simplicity. The inner and outer hoop reinforcement are modeled with 2-node truss elements with section area equal to the hoop reinforcement area per unit length. The reinforcement is located at 3 in. from the inner and the outer faces of the concrete section. Reinforcement elements are defined with linear elastic steel reinforcement material properties listed in the "Material Properties" Section. The surrounding rock in the FE model is modeled with 3-node and 4-node plane strain elements with a thickness of 1 in. Soil elements have variable sizes, ranging from 3 in. by 3 in. at the interface with concrete elements to approximately 70 in. by 70 in. at the rock boundary. Rock elements are modeled using linear elastic material with an elastic modulus of 2,500 ksi and a Poisson's ratio of 0.25, corresponding to an RQD of 75%. To capture slippage and/or tension separation between the concrete and the rock elements, a thin interface (about 0.1 in.) is introduced between them and connected with radial spring elements. The spring elements are defined with bi-linear high-compression and low-tension stiffness properties. Friction between the concrete lining and the surrounding rock is neglected.

ASR load is modeled using thermal expansion load such that the hoop and the through-thickness expansions are equal to 0.15 mm/m. Concrete swelling is modeled using thermal expansion load such that the hoop and the through-thickness expansions are equal to 0.1 mm/m. The outmost boundary of the rock elements is fixed in the FE model.

The FE analysis is conducted using the software ANSYS 15.0 Structural (2013).

Evaluation of Performance at RE

As shown in the proposed CDFM method incorporating the ASR effect, the 1% non-exceedance probability (NEP) point on the fragility curve is evaluated by performing evaluations of designated confidence levels of demands and capacities under different conditions. For non-ductile modes, which are applicable to tunnel linings crushing, this comparison is between the 99% exceedance probability (EP) elastic strength and 84% NEP demand.

EPRI 3002012994 (2018) specifies that the 99% EP elastic strength can be achieved by either of the following two combinations:

- 98% EP material properties and 95% EP static strength equations, or
- Design (minimum specified) material properties and strength design equations in design provisions with the recommended strength reduction factors of modern code (including ACI 318 (2019)).

The second combination is used in this case study to calculate the 99% EP elastic strength. The compressive crushing capacity based on ACI 318 (2019) is as follows:

$$P_u = \phi_c \cdot 0.8 \cdot \left[0.85 f_c' \left(A_g - A_s\right) + A_s f_y\right] \tag{1}$$

Where P_u represents axial design load in compression members, ϕ_c represents strength reduction factor for compression members, f_c' represents the concrete compressive strength, f_y represents the steel yield strength, and A_g, A_s represent the gross area and steel reinforcement areas, respectively.

The 1% NEP capacity, $PGA_{1\%}$, is calculated using Equation (2)

$$PGA_{1\%} = F_{S,CDFM} \cdot F_\mu \cdot PGA_{RE} \tag{2}$$

Where $F_{S,CDFM}$ represents the CDFM strength factor, which is calculated as $(S_{CDFM} - P_N)/P_{EQ}$, S_{CDFM} represents the CDFM strength, which in this case equals to P_u, calculated from Eq. (1), P_N and P_{EQ} represent CDFM demands from combined operating loads and seismic demand under RE, respectively, F_μ

represents the inelastic energy absorption factor, which is equal to 1.0 for non-ductile failure modes, PGA_{RE} represents the PGA for RE.

Acceptance Criterion 1 is satisfied if $PGA_{1\%}$ is greater than PGA_{RE}.

Evaluation of Performance at 150% RE

This acceptance criterion is evaluated by comparing the 10% NEP capacity, $PGA_{10\%}$, with $1.5PGA_{RE}$. The 10% NEP capacity is derived from the median (50% NEP) capacity, considering a lognormal distribution. The detailed steps are as follows:

1. Calculate the median EP elastic strength, S_{median}, using Equation (1) without the strength reduction factor and with median material properties presented in the "Material Properties" section.

2. Calculate the median strength factor, $F_{S,median}$, using the following equation:

$$F_{S,median} = \frac{S_{median} - P_N}{P_{EQ}} \tag{3}$$

In lieu of the true median, a conservative estimate of the median was efficiently determined by using the same P_{EQ} demands calculated in the CDFM evaluation, which correspond to 84% NEP.

3. Calculate the logarithmic standard deviation of the strength factor, β_c, using the equation below, where $Z_{1\%}$is the Z-score corresponding to 1% EP, i.e., $Z_{1\%} = 2.33$.

$$\beta_c = \frac{\ln\left(F_{S,median}/F_{S,CDFM}\right)}{|Z_{1\%}|} \tag{4}$$

4. Calculate the 10% NEP capacity, $PGA_{10\%}$, using the following equation, where $Z_{10\%}$is the Z-score corresponding to 10% EP, i.e., $Z_{10\%} = 1.28$:

$$PGA_{10\%} = F_{S,median} \cdot e^{Z_{10\%} \cdot \beta_c} \cdot PGA_{RE} \tag{5}$$

Acceptance Criterion 2 is satisfied if $PGA_{10\%}$ is greater than $1.5PGA_{RE}$.

Evaluation Results

Demands from normal operation loads and the RE are summarized in Table 1. The hoop stress in the concrete elements under ASR load is shown in Figure 2.

Using the approach described above, the 1% NEP and 10% NEP capacities are 0.56 g and 0.95 g, respectively. They are greater than the PGA_{RE} of 0.15 g and 150% PGA_{RE} of 0.23 g, respectively. Therefore, both acceptance criteria are satisfied.

Table 1: Axial Force demands from operating loads and the RE for probabilistic seismic evaluation

Load	Axial force, (lbf/in) (positive in tension)
Rock load	-1,000
Swelling	-5,540
ASR	-8,310
RE	-4,000

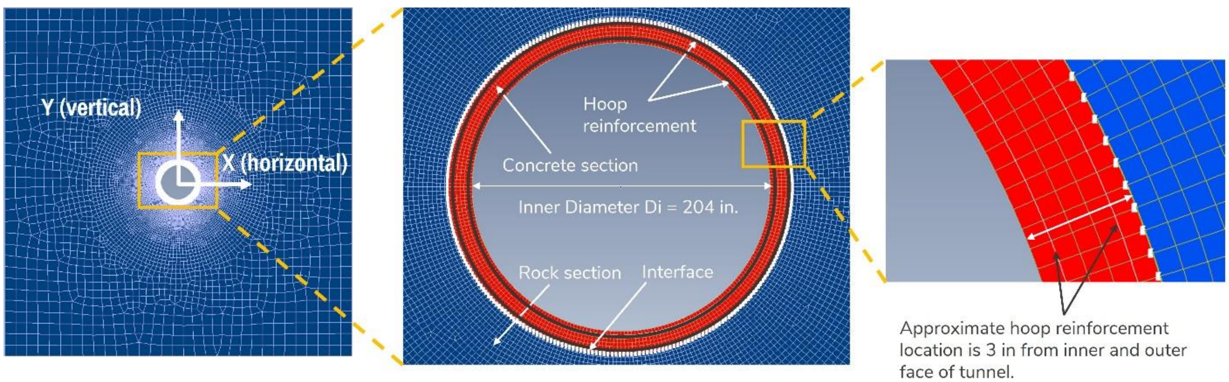

Figure 1. Finite element model of reinforced concrete tunnel in rock

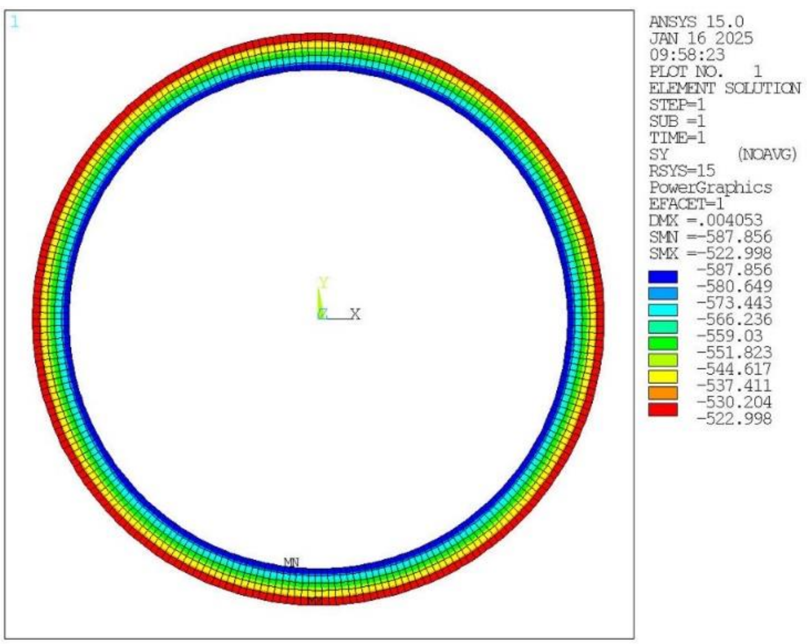

Figure 2. Hoop stress in concrete elements under ASR load

CONCLUSION

This paper presents a proposed framework for performing probabilistic seismic evaluation of reinforced concrete structures subjected to ASR with an application to tunnel linings. This framework is based on the CDFM method outlined in EPRI 3002012994 (2018). Results from the application of this framework to a seismic performance assessment of the reinforced-concrete tunnel linings considered to experience ASR are presented in this paper. The sum of seismic and non-seismic demands used in the CDFM is modified to incorporate the contribution of ASR-induced volumetric changes. The assessment demonstrated how the reinforced concrete tunnel meets the ASCE/SEI 43-19 (2019) acceptance criteria.

The philosophy for incorporating ASR into the CDFM method can be applied to other seismic fragility evaluation methods, for example, the Separation of Variables (SOV) approach outlined in EPRI 3002012994 (2018). The proposed framework can be adapted for probabilistic seismic evaluation of reinforced concrete structures experiencing other concrete-related degradation mechanisms.

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