

## SEISMIC FRAGILITY ESTIMATION OF BASE-ISOLATED NPP USING ARMA SYNTHESIZED LONG PERIOD GROUND MOTIONS

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### ABSTRACT

The study presents a procedure to artificially generate long-period ground motions using time-varying and time-invariant ARMA model approach. Since the recent destructive seismic motions of Tohoku earthquake seemed to possess the statistical features of non-stationary time series of a massive kind; a group of long-period ground motions of Tohoku earthquake is selected to develop the study. Moreover, the probabilistic risk assessment of a base-isolated NPP reactor containment building is investigated using the synthesized ground motions. The seismic fragility curves of the base-isolated NPP subjected to time-variant and time-invariant artificial ground motions are presented. The results compare the outcomes of ground motions of both types and hence ascertain the efficiency and reliability of the presented method.

### INTRODUCTION

On the seismic risk evaluation of NPP components, research studies reported by Kennedy *et al.* (1980), Kennedy and Ravindra (1984) have always been followed as the commendable state of the art. The derivation of fragility curves as a function of earthquake PGA and its comprehensive implication to assess the risk of NPP structural components through probabilistic approach was regarded as the premium highlight of their work. Since then, many diverse researches have been conducted on the parametric statistical evaluation of fragility plots, finding strength related factors of NPP and its seismic demand and capacity, dynamic responses analyses of NPP against real and artificial time histories incorporated with associated uncertainties (Zentner, 2010; Pisharady and Basu, 2010). After the catastrophic hit of Tohoku earthquake; majorly to the nuclear facilities of Japan, the current design practices for the safety provisions of nuclear structures are believed to be improved and require complete safety assurance; specifically for safety-related structures against such events. Although the studies encountering the substantial effects of real and artificially synthesized long-period ground motions as well as its synthetic simulation for the probabilistic risk analysis (PRA) of NPPs are limited, some appreciable researches on the generation of artificial time histories are as follows. A parametric ARMA model approach for the analysis and synthesis of the strong earthquake motions was demonstrated by Popescu and Demetriu (1990) and hence the use of results was suggested for the structural design. As a realization of real acceleration records, Conte *et al.* (1992) described the concept of discrete time-varying autoregressive moving average (ARMA) models to generate the non-stationary seismic motions. Kalman filter was used to estimate the time varying parameters of the model along with the consideration of non-stationarity in amplitude and frequency. A simplified time invariant ARMA (2, 1) model was successfully used by Mobarakeh *et al.* (2002) for artificial generation of seismic signals and the reproduction of non-stationary amplitude and frequency content of the acceleration data. Dong *et al.* (2004) proposed the time varying vector ARMA model based

method to synthesize several ground motions in the time and frequency domain using Kalman filter and shown nice agreement of the outputs with targeted ones. Later, the concept of unscented Kalman filtering was introduced for the time varying spectral analysis of the earthquake ground motions and to account for the effect of frequency resolving power of ARMA model on time varying spectrum (Dong *et al.*, 2009).

This paper presents a simple yet efficient synthesis of non-stationary long-period seismic records of Tohoku earthquake using time variant ARMA models. The spectral compatibility of original and artificially generated ground motions is checked to maintain the accuracy and precision. The PRA of based-isolated Korean NPP reactor containment building is performed to evaluate the seismic risk. Eventually, the outcomes of time variant ground motions are compared as well to emphasize on the efficacy and adequacy of the presented study.

## ARTIFICIAL SYNTHESIS OF SEISMIC MOTIONS

Since the study aims at showing the effects of non-stationary and stationary characteristics of earthquake signals, time-varying ARMA (TVARMA) and time invariant ARMA (TIVARMA) models are adopted to synthesize a group of long-period ground motions of Tohoku earthquake (Ali *et al.*, 2012). The set of ground motions selected are spectrally compatible with design response spectrum of United States Nuclear Regulatory Commission (USNRC) Guide 1.60.

A time-varying ARMA ( $p, q$ ) model as one of the tools to predict seismic time series ( $y_k$ ) can be presented as in Eqn.(1), where  $e_k$  is the unit-variance discrete Gaussian white noise ( $e_k \sim N(1, \sigma_{e,k}^2)$ ),  $\sigma_{e,k}^2$  is the envelope function of the noise and represents non-stationarity in amplitude,  $\phi_{i,k}$  and  $\theta_{i,k}$  are the time varying autoregressive (AR) and moving average (MA) coefficients, respectively and account for the non-stationarity in frequency content (Conte *et al.*, 1992). The subscript  $k$  denotes the instant  $t = k\Delta t$ , where  $\Delta t$  is the sampling time.

$$y_k - \phi_{1,k}y_{k-1} - \dots - \phi_{p,k}y_{k-p} = e_k - \theta_{1,k}e_{k-1} - \dots - \theta_{q,k}e_{k-q} \quad (1)$$

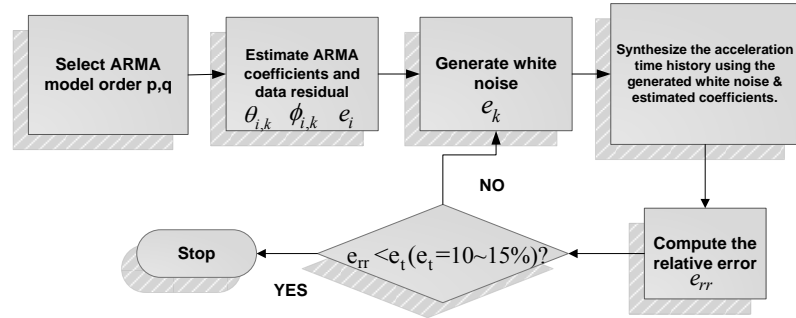


Figure1. Synthesis process

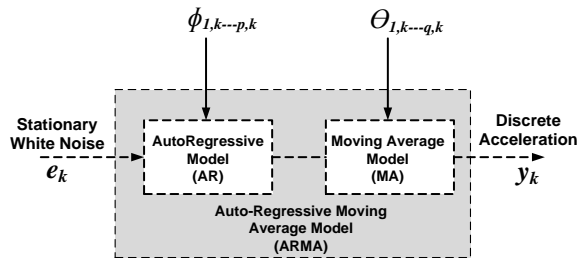


Figure2. ARMA model configuration

The process synthesizing long-period ground motions spectrally compatible with the targeted response spectrum of real records is shown in Figure 1 and explained as follows:

Step 1: Select the ARMA ( $p, q$ ) model order being an important factor the time-varying spectrum estimation.

Step 2: Estimate the time-varying ARMA coefficients  $\phi_{i,k}$ ,  $\theta_{i,k}$  and data residual  $e_i$  by filtering the acceleration record using Ormsby filter.

Step 3: Generate discrete normally distributed white noise  $e_k$  concurrent with the statistical distribution of the residual  $e_i$ .

Step 4: Synthesize the acceleration time history using the generated white noise  $e_k$ , estimated time-varying ARMA parameters  $\phi_{i,k}$ ,  $\theta_{i,k}$  as demonstrated in Figure 2.

Step 5: Check the spectral compatibility of the simulated output with the target spectrum by comparing the relative error  $e_{rr}$  with the threshold error  $e_t$  as follows.

$$e_{rr} = \sum_{k=1}^n \left| \frac{S_a(y_k) - S_a^T(y_k)}{S_a^T(y_k)} \right| \quad \therefore e_{rr} \leq (e_t = 10 \sim 15\%)$$

If the threshold error  $e_t$  is greater than the relative error  $e_{rr}$ , repeat the process from Step 3 followed by the regeneration of white noise. Moreover, for multiple generations, different white noises have to be generated accordingly in Step 3.

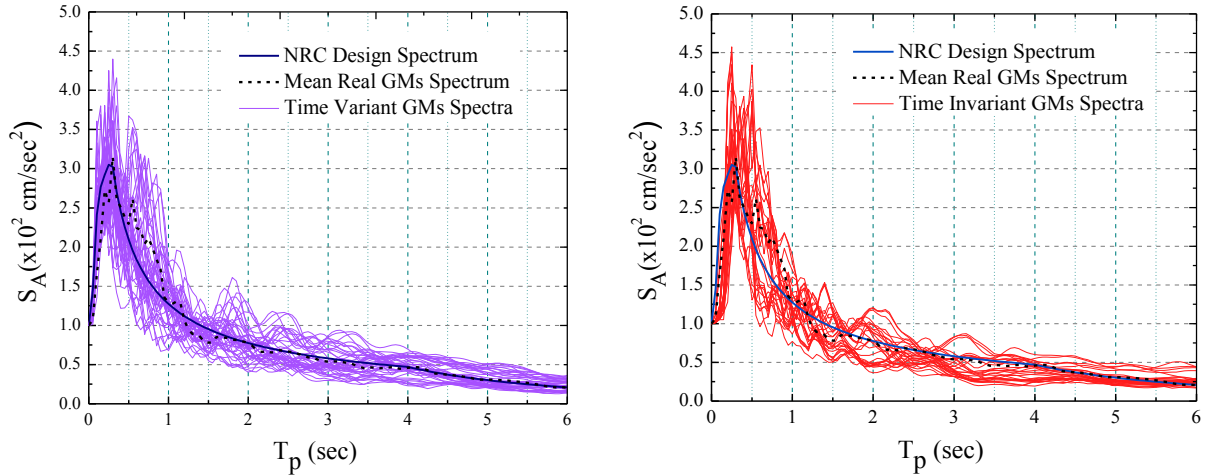


Figure 3. Compatibility representation of (a) Time Variant & (b) Time Invariant ground motion spectra with NRC design & Mean real ground motion spectrum

The synthesized time variant and time invariant seismic motions are compared with the mean real ground motion spectrum and NRC target spectrum as shown in Figure 3. Moreover, the mean spectral comparison of each type of ground motion with NRC spectrum is shown in Figure 4.

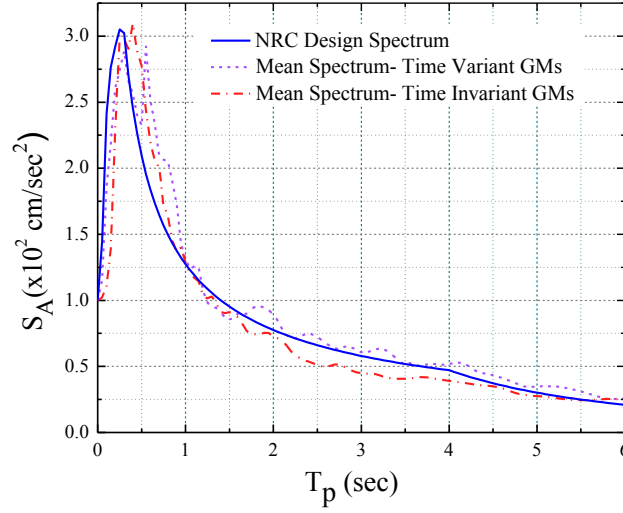


Figure 4. Mean spectral comparison

## PROBABILISTIC SEISMIC RISK ANALYSIS (PSRA) OF BASE-ISOLATED NPP

### *Structural Model of Base-Isolated NPP*

The base-isolated NPP reactor containment building represented by the lumped mass stick model, the hypothetical structural diagram, alongside with the characteristics of each node and element (Lee and Song, 1999) is depicted in Figure 5 (a). For analyses purposes, the model including 14 nodes and 15 elements is developed using Opensees platform (McKenna and Fenves, 2001). A zero-length isolator element with bilinear hysteretic material behavior is considered for the idealization of seismic isolation in the NPP stick model and is shown in figure 5 (b). The guidelines of Naeim and Kelly (1999) are followed to obtain the allowable displacement  $D_D$  of the isolator.

$$D_D = \frac{g}{4\pi^2} \frac{C_{VD}}{B_D} T_D \quad (2)$$

Where  $C_{VD}$  and  $B_D$  is the spectral seismic and damping coefficient, respectively and obtained from the appendix of 1997 UBC code,  $T_D$  refers to the natural period of the base isolated NPP.

### *Computation of Seismic Fragility*

To evaluate the seismic risk of the base-isolated NPP containment building, the artificial acceleration records synthesized by the stochastic models shown in earlier section are applied to obtain the maximum structural response of the NPP acknowledged as the displacement of the isolated node i.e. Node2. Each ground motion is scaled by its PGA ranging from 0.02 to 1.0g representing different excitation levels with an increment of 0.02g. The NPP fragility  $P_f$  is estimated at each excitation level  $a$  by taking the ratio of the number of times the maximum response exceeds a critical value to the total

number of seismic motions (Kim et al., 2012). The approach is more comprehensively formulated by Zentner (2010) as follows:

$$P_f(a) = \int_0^a \frac{1}{x\beta\sqrt{2\pi}} e^{-0.5\left(\frac{\log(x/A_m)^2}{\beta^2}\right)} dx = \Phi\left(\ln\left(\frac{a}{A_m}\right)/\beta\right) \quad (3)$$

Figure 6 shows the failure probability of the base-isolated NPP as a function of PGA at different seismic levels. States A, B and C are three limit states which are multiples of the allowable displacement  $D_D$  of the isolator i.e.  $0.5 D_D$ ,  $1.0 D_D$  and  $1.5 D_D$  respectively.

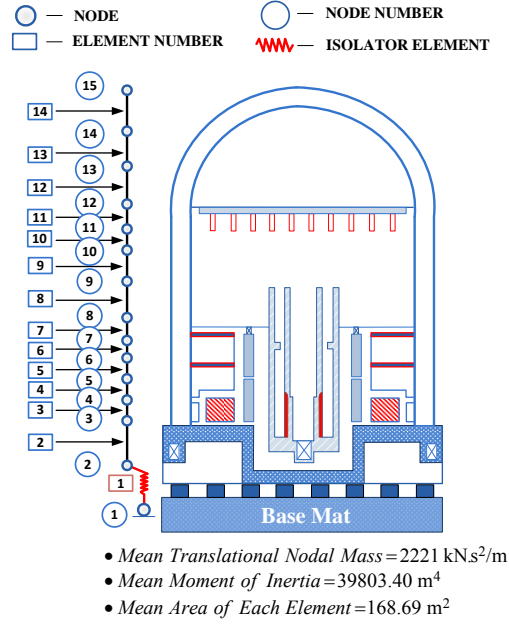
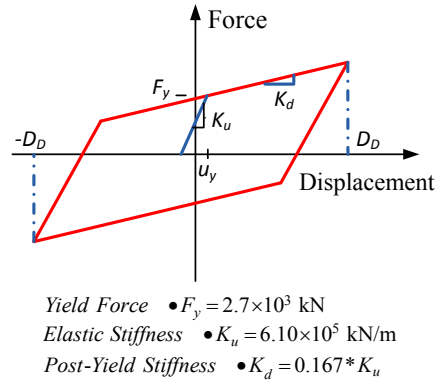


Figure 5 :(a) Stick model & Structural idealization of Base-Isolated NPP



(b) Hysteretic behavior of bilinear isolator

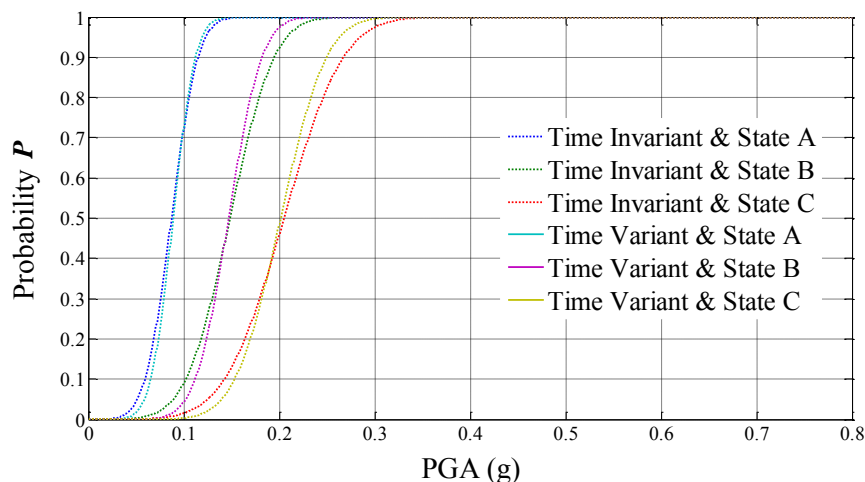


Figure 6. Fragility curves at Node 2 of the base isolated NPP

## CONCLUSION

The study focuses on the effects of non-stationary and stationary attributes of long-period ground motions on a base-isolated NPP containment building. Therefore, ARMA model approach is adopted to generate artificial long-period seismic motions using the acceleration records of Tohoku earthquake. Moreover, the influence of the artificially synthesized long-period seismic motions on the probabilistic seismic performance of NPP containment building incorporated with idealized seismic isolation; is evaluated. The inclusion of trapezoidal Ormsby filter in the process of seismic signals generation has simplified the estimation of the time-varying parameters of ARMA model and obtaining the time-varying spectrum. The spectral compatibility of the generated seismic motions is checked with the original records by means of a relative error of 10~15%.

Probabilistic seismic risk analysis (PSRA) has been performed to portray the effect of time-varying parameters on the failure probability of the base-isolated NPP comparative to the outcomes of the synthesized time-invariant ground motions. It can be noticed clearly from the fragility curves presented in the study that the base-isolated NPP shows higher risk under the non-stationary long-period ground motions than the stationary signals and hence emphasize the adequacy and efficiency of the proposed approach. Moreover, it requires more extensive research to better understand the devastating long-period character of long-period motions of Tohoku earthquake and demands revised seismic design standards to assure the safety of nuclear facilities in the future.

## ACKNOWLEDGMENTS

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