Review of Non-Ergodic Ground Motion Model Development for Site-Specific Seismic Hazard Assessment

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1. Introduction

The Ground Motion Model (GMM) provides predictions of ground-motion intensity for given earthquake magnitude and source-to-site distance conditions and is primarily used within Probabilistic Seismic Hazard Analysis (PSHA) to estimate seismic hazard levels. Traditionally, most GMMs have been developed under the ergodic assumption, combining data from multiple earthquakes and recording stations while treating source, path, and site variability as random effects represented by a single median prediction and overall standard deviation. However, this framework does not fully account for systematic site- or source-specific characteristics. In response, non-ergodic GMMs that explicitly account for site, path, and source characteristics have been actively developed in recent years [1-3]. This approach aims to explicitly incorporate site, path, and source-specific characteristics into the median prediction equation, thereby improving predictive accuracy and rationally reducing the standard deviation, that is, aleatory uncertainty.

Figure 1(a) illustrates the probability density functions of predicted Spectral Acceleration under identical conditions. The non-ergodic GMMs show narrower distributions with different medians. Figure 1(b) compares seismic hazard curves derived from each model. Even when the median prediction is similar, the non-ergodic GMM yields lower hazard values in the high ground-motion range due to its reduced standard deviation. This tendency contributes to reduced conservatism and more realistic hazard estimates.

Since seismic hazard results serve as fundamental input parameters for the design and safety assessment of nuclear installations, the use of non-ergodic models enables more precise prediction of site-specific seismic behavior and provides a scientific basis for optimizing both safety and economic efficiency in nuclear facility design [4].

In this study, the procedures required for developing a non-ergodic GMM are systematically summarized through a literature review.

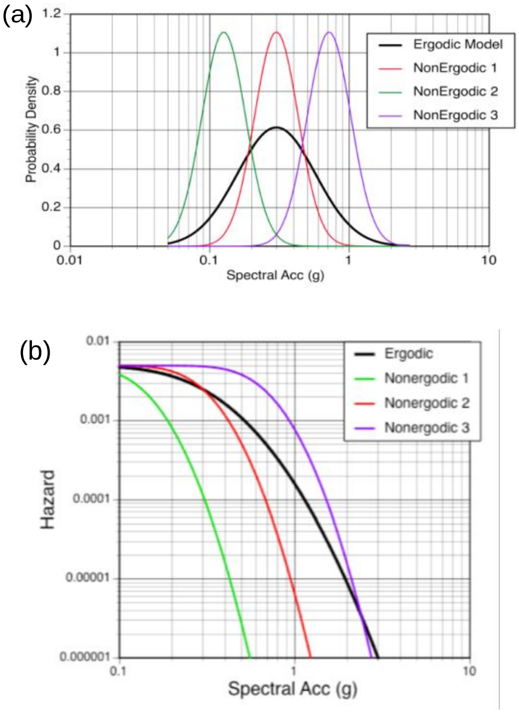

Fig. 1. (a) Probability density functions and (b) hazard curves of ergodic and non-ergodic GMMs [5].

2. Procedure for Developing a Non-Ergodic GMM

2.1 Collection of Ground-Motion Records and Site Information

Ground-motion records for developing a non-ergodic GMM should be processed in accordance with current international standards[6,7], and usable frequency ranges should be determined individually through signal-to-noise ratio (SNR) analysis rather than fixed filtering.

Since non-ergodic terms are derived from residuals between observations and ergodic GMM predictions, reliable source and site information is essential. Key metadata include moment magnitude (M_w), hypocenter location and depth, V_{S30} and shear-wave velocity profiles, bedrock depth, faulting mechanism, stress parameter, and regional attenuation and velocity structure.

2.2 Calculation of Residuals Relative to a Backbone Ergodic GMM

A fundamental step in the development of a non-ergodic GMM involves the quantitative characterization of systematic residual patterns between observed ground motions and the median predictions of a backbone ergodic GMM. For the first step, a backbone ergodic GMM is selected, and predicted ground-motion values are calculated for each record. The ergodic GMM typically includes magnitude M, distance R, and sometimes simple site proxies such as V_{S30}. Regional, site-specific, and path-specific effects are not explicitly separated; instead, all data are represented by a single average empirical relationship.

For each earthquake event and station, the residual is defined as the difference between the natural logarithm of the observed intensity measure $\ln(Y)$ and the logarithm of the median prediction $\ln(\mu_{erg}(M, R, \ldots))$. This residual contains all effects not captured by the ergodic model.

For a given earthquake event, the average residual across all recording stations is defined as the between-event residual, representing the extent to which the event is stronger or weaker than expected relative to the average source characteristics. On the other hand, the deviation at an individual station is defined as the within-event residual, which is interpreted as the combined effect of path and site conditions.

2.3 Residual Analysis and Introduction of Non-Ergodic Terms

If a station consistently exhibits positive or negative residuals across multiple events, this pattern can be interpreted as deterministic information that may be incorporated into the median prediction under a non-ergodic framework. For example, in developing a non-ergodic GMM with a site term, correlations between site-specific residuals and site parameters such as V_{S30}, bedrock depth, or average shear-wave velocity are analyzed. If statistically significant relationships are identified, a site term $\delta S2S$ can be introduced into the median prediction equation. Introducing path and source terms is more complex. Path effects require multiple stations recording the same event and accounting for structural heterogeneity along propagation paths. Source effects require sufficient numbers of events recorded at common stations to resolve event-specific characteristics. These components typically require more extensive datasets and regional geological modeling, making their implementation more demanding than site-term corrections. A fully non-ergodic GMM estimates source, path, and site effects individually for each region or location, thereby minimizing the standard deviation and improving spatial consistency and statistical precision. A partially non-ergodic GMM incorporates some of these factors into the median prediction. Figure 2 presents a structured summary of the components included in the ergodic GMM, partially non-ergodic GMM, and fully non-ergodic GMM, together with the way the corresponding residuals are defined and decomposed in each framework.

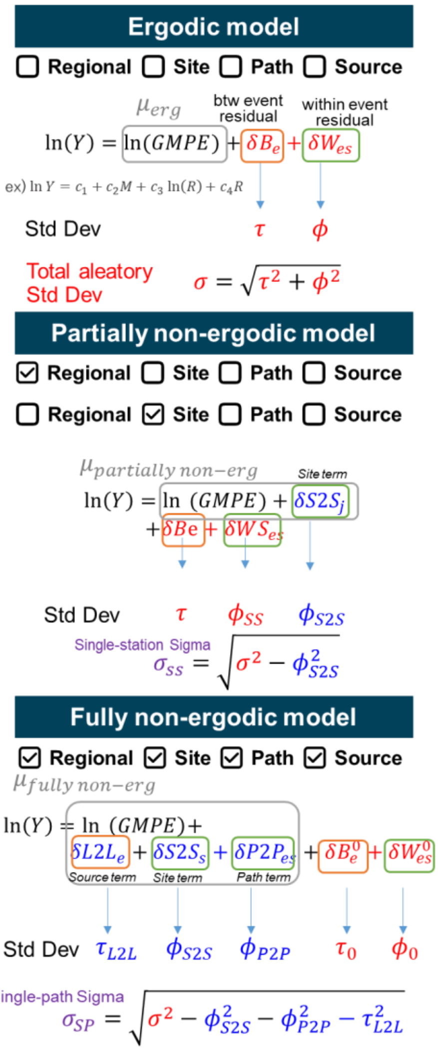

Fig. 1. (a) Probability density functions and (b) hazard curves of ergodic and non-ergodic GMMs [5].

2.4 Quantification of Aleatory Uncertainty

Uncertainty in non-ergodic GMMs is broadly classified into two types. First, aleatory uncertainty arises from inherent physical variability in earthquake occurrence, wave propagation, and site response. This type of uncertainty cannot be completely eliminated. Second, epistemic uncertainty results from limited data, model selection, and incomplete understanding of source and site characteristics; it can be reduced through additional observations and research.

when introducing a non-ergodic site term, the average site term δS2Ss becomes part of the median model. Consequently, the corresponding variance component is no longer treated as aleatory uncertainty, and a single-station standard deviation is defined. In fully non-ergodic GMMs, source and path effects are also incorporated, further reducing aleatory uncertainty.

Lin et al. [8] reported that removing only the site term reduces the single-station standard deviation by approximately 10–15%, whereas incorporating site, path, and source terms can reduce the ergodic standard deviation by 40–50%.

2.5 Quantification of Epistemic Uncertainty

In the non-ergodic framework, systematic source, path, and site effects are transferred from aleatory variability to the median prediction model. As a result, aleatory uncertainty decreases, whereas epistemic uncertainty increases because non-ergodic terms must be estimated from limited data.

The logic-tree method assigns expert-judgment-based weights to multiple candidate GMMs, allowing alternative scientific interpretations to be considered in parallel. The scaled backbone approach selects a single backbone model representative of regional characteristics and statistically adjusts it within a justifiable range to represent uncertainty; this approach has been applied in the AG model and PSBAH model of NGA-Sub [9,10]. Bayesian inference estimates posterior distributions of regression coefficients, enabling quantitative and reproducible uncertainty evaluation [11]. Sammon’s mapping is a nonlinear dimensionality-reduction technique that visualizes dissimilarities among candidate GMMs in a two-dimensional space and assists in selecting representative models [12].

3. Conclusions

This study systematically organized the procedures required to develop a non-ergodic Ground Motion Model (GMM), from data collection and residual decomposition to the quantification of aleatory and epistemic uncertainties. The core distinction between ergodic and non-ergodic frameworks lies in how variability is treated. Under the ergodic assumption, source, path, and site effects are collectively represented within a single median prediction and total standard deviation. In contrast, the non-ergodic approach explicitly models repeatable source-, path-, and site-specific characteristics and transfers these systematic effects from random variability into the median prediction equation. Incorporating site terms, and when data allow, path and source terms, leads to substantial reductions in aleatory uncertainty.

For nuclear installation sites, where seismic hazard results directly govern design margins and safety evaluations, Non-ergodic GMMs enable site-specific hazard characterization, decrease unnecessary conservatism in high ground-motion ranges, and provide a scientifically defensible balance between safety assurance and economic efficiency.

Consequently, developing non-ergodic GMMs is a critical advancement for risk-informed nuclear facility design and long-term safety management.

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