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From Probabilistic Compliance to Event-Validated Resilience: A Governance-Centric Framework for Seismic Hazard Assessment in Critical Infrastructure Systems

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Abstract

Seismic hazard assessment (SHA) has historically relied on probabilistic (PSHA) and deterministic (DSHA/NDSHA) methodologies to inform engineering design and risk mitigation. While ongoing debate has focused on the relative merits of these approaches, both paradigms exhibit limitations when evaluated through the lens of real-world system performance. This paper advances the discourse by reframing seismic hazard assessment as a governance and validation problem rather than a purely probabilistic or deterministic modeling challenge. Building upon prior work introducing the S-E-R-M Framework, this study proposes an extended model—S-E-R-M-V (Validation)—that integrates event-based falsification, adaptive hazard recalibration, and feedback-driven resilience engineering into seismic risk governance. The framework incorporates design magnitude (Mdesign) as a structural boundary condition while embedding real-event validation across infrastructure, emergency management, and policy systems. The result is a forward-leaning paradigm that transcends the PSHA versus NDSHA dichotomy by aligning hazard modeling with operational performance, infrastructure survivability, and governance accountability.

Keywords: Seismic hazard assessment; resilience engineering; critical infrastructure; governance; NDSHA; PSHA; validation

1. Introduction

Seismic hazard assessment has traditionally been framed as a technical exercise in estimating ground motion using probabilistic seismic hazard assessment (PSHA) and deterministic/neo-deterministic seismic hazard assessment (DSHA/NDSHA) approaches (Baker et al., 2021; Panza & Bela, 2020; Reiter, 1990). While these approaches provide essential inputs for engineering design and planning, they are rarely evaluated against **observed system performance during real seismic events**, creating a persistent gap between modeled risk and operational outcomes (Rugarli et al., 2019; Stark, 2022).

This limitation is particularly consequential for critical infrastructure systems, where failure is determined not by probabilistic thresholds but by **actual structural performance, coordination effectiveness, and system resilience under stress conditions** (Federal Emergency Management Agency [FEMA], 2021; U.S. Geological Survey [USGS], 2022a).

Prior work introduced the S-E-R-M Framework as an integrative model that aligns structural systems, emergency management, risk communication, and monitoring technologies to support seismic preparedness and risk reduction. However, that framework did not explicitly incorporate a mechanism for evaluating hazard models against real-world outcomes.

The present study advances that work by introducing **S-E-R-M-V**, a governance-centric extension that embeds validation as a core system function. Unlike prior descriptive and integrative approaches, this model establishes a **performance-based, feedback-driven system** that continuously aligns hazard modeling with observed infrastructure and operational performance. This shift positions seismic hazard assessment as an adaptive governance process consistent with resilience engineering principles (Hollnagel, 2014; Weick & Sutcliffe, 2015).

2. Methodology

This study employs a structured analytical methodology consistent with engineering-management research standards.

2.1 Structured Document Analysis

Peer-reviewed literature on seismic hazard modeling, infrastructure resilience, and engineering design was systematically analyzed to identify:

- assumptions underlying PSHA and NDSHA
- limitations in validation mechanisms
- implications for infrastructure performance and governance systems (Baker et al., 2021; Panza et al., 2022)

2.2 Comparative Analytical Framework

Rather than employing descriptive case-study methods, this study uses a **comparative analytical approach**, treating seismic events as performance benchmarks. This enables evaluation of:

- system-level response effectiveness
- structural performance thresholds
- operational coordination outcomes
- communication system reliability

2.3 Conceptual Hazard–Governance Integration Model

PSHA and NDSHA are evaluated as complementary inputs within a governance system that incorporates:

- probabilistic uncertainty (PSHA)
- deterministic boundary conditions (Mdesign via NDSHA)
- validation through observed system performance

The validation loop illustrated in Figure 2 provides the operational mechanism for evaluating hazard models against observed system performance.

3. Limitations of Current Seismic Hazard Paradigms

3.1 PSHA: Non-Falsifiable Risk Modeling

PSHA provides probabilistic estimates but cannot be empirically falsified because of non-zero exceedance probabilities, thereby limiting its effectiveness in validation-driven systems (Stark, 2022; Panza & Bela, 2020).

3.2 NDSHA: Deterministic Boundary Without System Integration

NDSHA introduces physically grounded hazard envelopes through Mdesign, enabling comparison between modeled and observed events (Rugarli et al., 2019). However, it does not inherently account for:

- infrastructure interdependencies
- operational performance variability
- governance adaptation

3.3 Structural Gap: Absence of Feedback Mechanisms

Both approaches lack:

- closed-loop validation
- system-wide performance assessment
- adaptive recalibration mechanisms

This results in static hazard models within dynamic risk environments (Hollnagel, 2014).

4. The S-E-R-M-V Framework

4.1 Framework Advancement

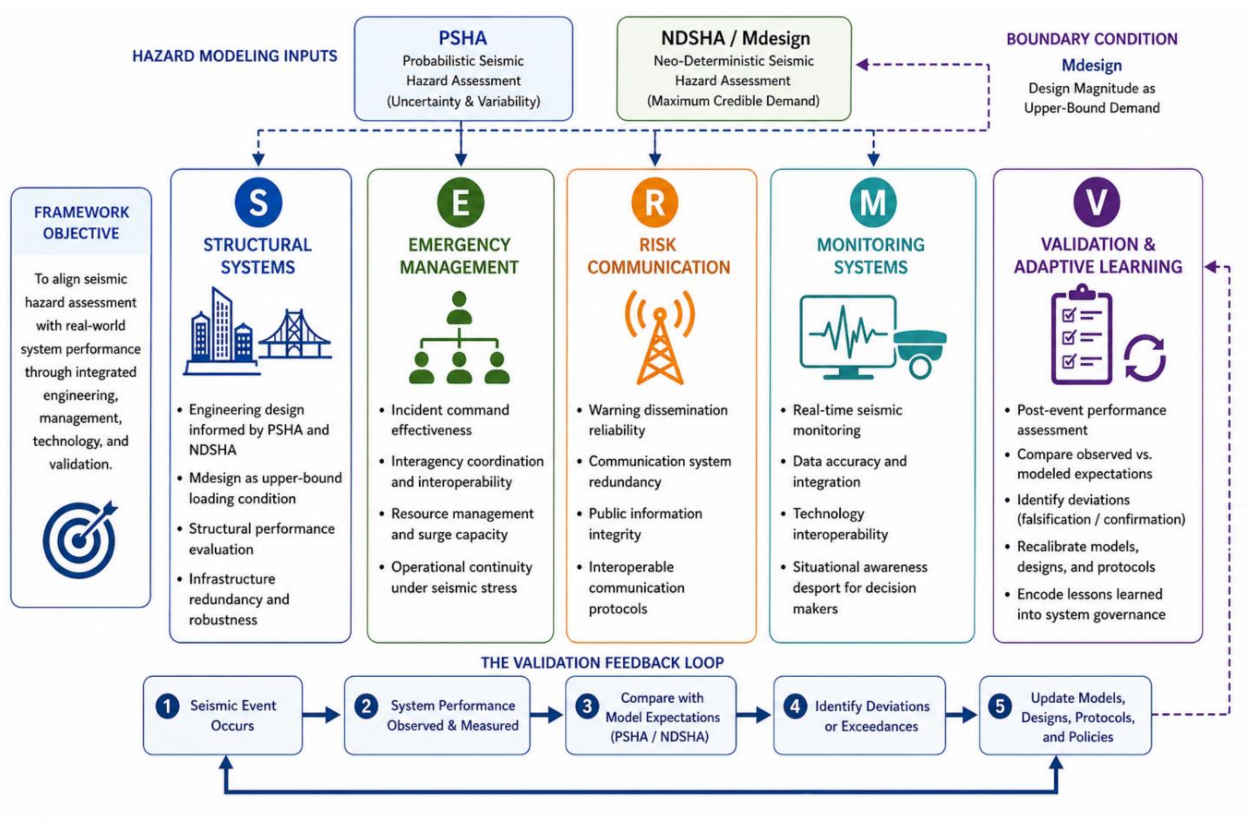
The S-E-R-M-V Framework extends prior work by introducing **Validation (V)** as a core system function, transforming seismic hazard assessment into a continuous, performance-based governance model.

- Structural Systems (S)
- Emergency Management (E)
- Risk Communication (R)
- Monitoring Systems (M)
- Validation & Adaptive Learning (V)

To operationalize the proposed governance-centric extension, the integrated S-E-R-M-V framework is presented in Figure 1, illustrating the relationship between hazard modeling inputs, system-level domains, and the validation feedback loop that enables adaptive resilience.

Figure 1

S-E-R-M-V Framework for Event-Validated Seismic Resilience



Note. Author created. The figure illustrates the integration of probabilistic (PSHA) and deterministic (NDSHA) hazard-modeling inputs across five system domains—Structural Systems (S), Emergency Management (E), Risk Communication (R), Monitoring Systems (M), and Validation (V). The validation feedback loop demonstrates how observed seismic events inform assessments of system performance, model comparisons, the identification of deviations, and iterative updates to infrastructure design, operational protocols, and governance mechanisms.

Figure 1 demonstrates that seismic resilience cannot be achieved through isolated hazard modeling approaches or independent operational systems alone. Instead, effective resilience emerges through the continuous integration of structural engineering, emergency management, risk communication, monitoring technologies, and validation-driven governance processes operating within a unified adaptive framework. The S-E-R-M-V model, therefore, positions resilience as a dynamic system capability sustained through ongoing coordination, feedback, and institutional adaptation across interconnected infrastructure domains.

4.2 Structural Systems (S): Engineering Boundary Conditions

As illustrated in Figure 1, the S-E-R-M-V framework establishes a closed-loop system in which hazard modeling, infrastructure performance, and governance mechanisms are continuously aligned through validation-driven feedback.

Structural design integrates:

- PSHA for probabilistic variability
- NDSHA (Mdesign) as a maximum credible loading threshold (Rugarli et al., 2019; Baker et al., 2021)

4.3 Emergency Management (E): Operational Effectiveness

System performance is evaluated through:

- coordination efficiency
- command structure execution
- resource deployment scalability (FEMA, 2021)

4.4 Risk Communication (R): System Reliability

Communication systems are assessed through:

- transmission integrity
- redundancy
- system resilience under stress (Mileti & Sorensen, 1990; Kırcı et al., 2023)

4.5 Monitoring Systems (M): Detection and Integration

Monitoring technologies provide the operational foundation for real-time hazard awareness, environmental sensing, seismic detection, and infrastructure-status monitoring. Advances in seismic instrumentation, intelligent sensor systems, and AI-assisted monitoring architectures increasingly enable organizations to detect evolving seismic conditions, assess infrastructure performance, and support time-sensitive operational decision-making (Li, 2021a, 2021b; Roy et al., 2024).

However, monitoring systems alone do not inherently produce resilience. Their effectiveness depends on integration into broader decision-making, emergency-management, and governance structures capable of translating technical observations into coordinated operational responses and adaptive resilience strategies. Within the S-E-R-M-V framework, monitoring systems function not only as detection mechanisms but also as continuous sources of information that support validation, operational coordination, infrastructure assessment, and governance adaptation during and after seismic events.

4.6 Validation (V): Closed-Loop Governance Mechanism

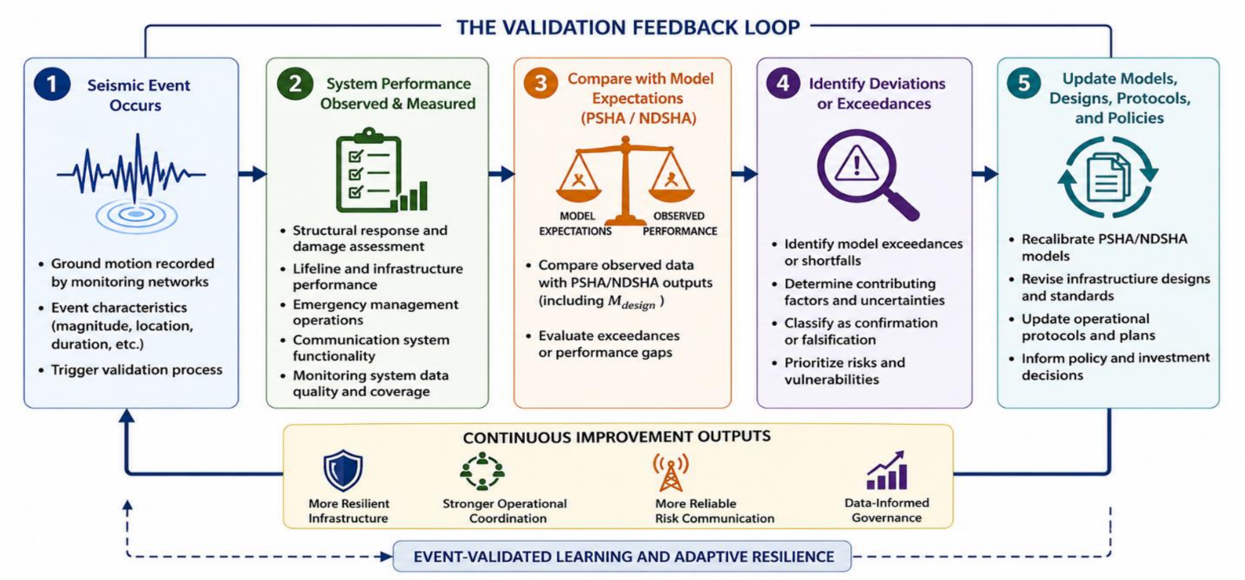
Validation metrics may include infrastructure recovery time objectives (RTO), interoperability success rates across emergency-management systems, communication-system continuity, structural survivability thresholds, and operational restoration timelines. These indicators provide measurable benchmarks for evaluating the effectiveness of hazard models and governance adaptation mechanisms following seismic events. By incorporating measurable operational outcomes into the assessment process, the framework transforms seismic hazard evaluation into a continuous, adaptive, and performance-oriented governance system consistent with resilience-engineering principles (Hollnagel, 2014).

To further clarify the operational structure of this process, the validation feedback loop is isolated and illustrated in Figure 2 as a continuous, event-driven mechanism for system evaluation and adaptive improvement.

Governance accountability within the validation process may involve coordinated oversight among infrastructure regulators, emergency-management agencies, engineering review authorities, and public-sector resilience offices responsible for updating hazard assumptions, operational procedures, infrastructure standards, and resilience policies following validated system deviations or exceedance events. Effective governance coordination ensures that validation outcomes are not treated as isolated technical observations but as institutional decision signals that inform resilience-policy adaptation, infrastructure modernization, operational continuity planning, and long-term risk-governance strategies across interconnected critical infrastructure systems.

Figure 2

Validation Feedback Loop for Event-Driven Seismic Resilience



Note. Author created. The figure presents the validation component of the S-E-R-M-V framework as a closed-loop process consisting of five stages: (1) seismic event occurrence, (2) system performance observation and measurement, (3) comparison of observed outcomes with hazard model expectations (PSHA/NDSHA), (4) identification of deviations or exceedances, and (5) updating of models, infrastructure designs, operational protocols, and governance policies. The loop emphasizes continuous improvement through iterative system adaptation based on real-world performance.

As illustrated in Figure 2, validation operates as a continuous feedback mechanism that transforms seismic events into actionable system intelligence, enabling iterative refinement of hazard models, infrastructure design, operational coordination mechanisms, and governance strategies. Rather than functioning as a static post-event assessment, validation within the S-E-R-M-V framework serves as a dynamic resilience-learning system, through which observed operational outcomes continuously inform adaptive infrastructure governance and long-term system evolution.

For example, the 1994 Northridge earthquake demonstrated that real-world infrastructure and emergency-management performance can serve as validation signals for seismic hazard governance systems. Within the S-E-R-M-V framework, observed structural failures, communication disruptions, and operational coordination challenges would serve as measurable indicators for reassessing hazard assumptions, infrastructure design thresholds, emergency-response protocols, and governance adaptation strategies. In this context, seismic events operate not only as disasters to be managed, but also as system-level performance benchmarks that support iterative resilience improvement and hazard-model recalibration.

Within the S-E-R-M-V framework, validation extends beyond traditional engineering verification to function as a multi-dimensional governance-learning mechanism. At the technical level, validation evaluates the consistency between modeled seismic expectations and observed infrastructure performance. Operationally, validation assesses the effectiveness of emergency coordination, communication reliability, monitoring integration, and restoration capabilities under real-event conditions. From a governance perspective, validation functions as an adaptive recalibration process through which observed system outcomes inform the iterative refinement of hazard assumptions, infrastructure standards, emergency-management procedures, and resilience policies. This integrated approach aligns with resilience engineering and Safety-II principles by treating deviations, exceedances, and operational disruptions not solely as failures but as system-learning signals that can strengthen long-term infrastructure resilience and governance adaptation.

5. Event-Validated Resilience

This study redefines resilience as **the measurement of system performance under real seismic conditions**, rather than theoretical compliance with hazard models.

5.1 Falsification as System Signal

Exceedance of Mdesign or system failure constitutes:

- model failure
- governance failure
- system redesign trigger (Rugarli et al., 2019)

Within the S-E-R-M-V framework, falsification is not interpreted solely as invalidation of a hazard model, but as a system-level governance signal indicating the need for adaptive reassessment of infrastructure assumptions, operational coordination mechanisms, resilience policies, and institutional preparedness strategies. In this context, exceedance events function as empirical learning mechanisms that support iterative resilience improvement across interconnected infrastructure and governance systems.

5.2 Adaptive System Evolution

The framework supports:

- iterative infrastructure improvement
- policy evolution
- system redesign

This aligns with resilience engineering and Safety-II principles (Hollnagel, 2014; Weick & Sutcliffe, 2015).

6. Implications for Critical Infrastructure Systems

6.1 Transition from Compliance to Performance

Infrastructure systems must shift toward performance-based resilience frameworks (National Institute of Standards and Technology [NIST], 2016).

Importantly, the S-E-R-M-V framework is not intended to replace existing FEMA guidance, ISO resilience standards, or national seismic design frameworks. Rather, the model functions as an adaptive governance overlay that integrates validation-driven learning and performance-based resilience assessment into existing regulatory and infrastructure-management systems.

6.2 Cross-Domain Integration

The framework aligns engineering systems, emergency management, and governance structures into a unified operational model.

Effective implementation of the S-E-R-M-V framework requires coordinated governance structures capable of integrating engineering assessment, emergency-management oversight, infrastructure regulation, and resilience-policy adaptation into a unified decision-making process. Following significant seismic events or validated system deviations, governance entities may be responsible for initiating infrastructure reassessment procedures, updating hazard assumptions, revising operational continuity protocols, and implementing resilience-improvement strategies across interconnected infrastructure systems. This integrated governance structure supports institutional accountability while enabling adaptive system evolution in response to observed operational performance.

6.3 Applicability to Modern Systems

The model applies directly to:

- cyber-physical systems
- smart infrastructure environments
- AI-enabled monitoring architectures (NIST, 2023)

7. Discussion

The PSHA vs. NDSHA debate represents a **methodological false dichotomy**. Both approaches serve as inputs to a broader governance system, while validation assesses real-world effectiveness (Panza & Bela, 2020).

Within the proposed governance-centric framework, PSHA and NDSHA are not treated as competing endpoints but as complementary analytical inputs operating within a broader adaptive resilience system. PSHA provides a probabilistic characterization of uncertainty and variability, while NDSHA provides deterministic boundary conditions through physically grounded maximum-credible-event modeling. However, neither approach alone determines the effectiveness of resilience. Instead, resilience is ultimately evaluated through observed system performance during real seismic events, including infrastructure survivability, operational continuity, emergency-management coordination, communication-system reliability, and governance adaptation. In this context, validation becomes the operational mechanism through which hazard assumptions are continuously reassessed against empirical system outcomes, enabling iterative refinement of infrastructure design, operational protocols, and resilience governance strategies.

The proposed framework also aligns with resilience-engineering and Safety-II perspectives that emphasize the capacity of complex systems to adapt, learn, and maintain operational functionality under stress conditions (Hollnagel, 2014; Weick & Sutcliffe, 2015). Rather than treating seismic events solely as failures of prediction or compliance, the S-E-R-M-V framework conceptualizes disruptive events as opportunities for system learning, governance adaptation, and resilience enhancement. This perspective shifts seismic hazard assessment away from static compliance verification toward continuous organizational adaptation informed by observed operational performance and iterative infrastructure learning processes.

8. Conclusion

This study advances seismic hazard assessment beyond methodological preference by introducing a governance-centric framework integrating validation, performance measurement, and adaptive learning. The validation loop presented in Figure 2 represents the operational core of the S-E-R-M-V framework, linking hazard modeling directly to observed system performance and governance adaptation. The S-E-R-M-V Framework establishes seismic risk management as a continuous, evidence-based system, enabling infrastructure resilience to evolve through real-world events rather than static assumptions (Shawe, 2025).

As critical infrastructure systems become increasingly interconnected, technologically dependent, and exposed to complex cascading risks, resilience can no longer be defined solely through probabilistic compliance or static engineering assumptions. The S-E-R-M-V framework advances a transition toward adaptive, event-validated governance systems in which real-world performance continuously informs infrastructure design, operational coordination, emergency-management strategy, and resilience policy evolution. By embedding validation, feedback-driven learning, and governance adaptation into seismic hazard assessment, the framework establishes a forward-looking model for aligning infrastructure resilience with the dynamic realities of modern risk environments.

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