

## **Earthquake Science: Causes, Impacts, and Community Preparedness in the Modern Era**

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### **Abstract**

Earthquakes remain among the most damaging natural hazards, with impacts governed by local geology, the built environment, and preparedness. This review links core seismology concepts—fault mechanics, wave propagation, and modern monitoring—to community-level risk reduction. Analyzing three U.S. events (1906 San Francisco, 1964 Alaska, 1994 Northridge), distilled lessons for code updates, drills, and public communication. The outline advances in dense sensing, fibre-optic systems, and intelligent detection, and discusses how deterministic (NDSHA) and probabilistic (PSHA) approaches can be combined for planning. The result is a practical framework for translating science into policy actions that reduce casualties and infrastructure losses.

**Keywords:** earthquakes; seismic hazard; monitoring; PSHA/NDSHA; preparedness; risk communication.

## **Earthquake Science: Causes, Impacts, and Community Preparedness in the Modern Era**

### **Introduction**

Earthquakes remain among the most destructive natural hazards affecting modern society, causing large-scale human, economic, and infrastructural impacts. While the physical mechanisms driving seismic events are well established, the challenge for contemporary engineering and emergency management lies in translating seismological knowledge into actionable frameworks that reduce casualties and strengthen community resilience. Although extensive scientific literature exists on earthquake physics, seismic monitoring, and hazard assessment, fewer studies integrate these domains into a unified engineering-management perspective suitable for operational use by policymakers, planners, and emergency coordinators.

This study addresses that gap by examining how earthquake science, monitoring technologies, and hazard assessment techniques can be aligned with risk-management principles to improve preparedness and reduce losses. Through a comparative review of three major U.S. earthquakes (1906 San Francisco, 1964 Alaska, and 1994 Northridge), this paper evaluates how lessons learned have influenced building codes, emergency communication systems, and hazard-

mitigation strategies. A combined analytical framework incorporating both deterministic (NDSHA) and probabilistic (PSHA) approaches is introduced to illustrate where engineering and management decisions require different levels of certainty.

The purpose of this paper is not merely to describe earthquakes, but to develop an integrative model—grounded in seismology, engineering, and emergency management—that supports evidence-based planning for modern seismic risk.

### **Causes of Earthquakes**

Earthquakes occur when accumulated stress along a fault or plate boundary exceeds the strength of the surrounding rock, resulting in sudden rupture and energy release. Although the underlying geophysical mechanisms are well established, the significance of earthquake causation for emergency management and engineering lies not in the physical event itself, but in the predictability of rupture zones, recurrence patterns, and the implications for hazard modelling.

From a risk-management perspective, the most consequential cause of earthquakes is **tectonic plate interaction**, particularly in strike-slip, normal, and thrust faulting environments, which generate characteristic ground-motion profiles. These profiles inform engineering design spectra, retrofitting priorities, and scenario-based hazard assessments (e.g., PSHA and NDSHA). Volcanic or induced seismicity plays a comparatively minor role in broad-scale community risk and is therefore less central to preparedness planning.

Understanding earthquake causation enables planners and engineers to estimate the **expected intensity, duration, and frequency** of shaking in a given region. This supports decisions on building-code enforcement, infrastructure resilience, emergency-response planning, and the installation of early-warning systems. Thus, the importance of earthquake causes in this manuscript is not descriptive but analytical—providing the scientific basis for the risk-reduction frameworks and management strategies evaluated in subsequent sections.

### **Methodology**

This study employs an integrated qualitative–analytical methodology combining (1) structured document analysis, (2) comparative case analysis, and (3) conceptual hazard-assessment modelling. The objective is to evaluate how scientific knowledge, technological advancements, and management practices converge to shape earthquake preparedness and resilience.

#### **1. Structured Document Analysis**

Peer-reviewed seismology literature, engineering guidelines (FEMA, USGS, NEHRP), and hazard-assessment reports were systematically reviewed to extract:

- quantitative ground-motion parameters,
- technological capabilities of modern monitoring systems,
- engineering code developments across the 20th and 21st centuries.

## **2. Comparative Case Analysis (QCA)**

Three major earthquakes (San Francisco 1906, Alaska 1964, Northridge 1994) were analyzed using standardized variables:

- magnitude and intensity measures,
- infrastructure failure modes,
- emergency communication performance,
- building-code implications,
- long-term seismic-resilience outcomes.

## **3. Conceptual Hazard-Assessment Modelling**

Two established seismic-hazard paradigms were compared:

- **Probabilistic Seismic Hazard Assessment (PSHA)**: long-term frequency-based estimation
- **Neo-Deterministic Seismic Hazard Assessment (NDSHA)**: scenario-based ground-motion simulation

The goal is not to compute detailed hazard maps, but to demonstrate how each method supports different decision-making needs in engineering design, emergency preparedness, and land-use planning. This methodology shifts the paper from a descriptive essay to a structured, analytical study consistent with the expectations of engineering and management research.

### ***S-E-R-M Framework for Earthquake Risk Reduction***

#### **(Structural Measures – Emergency Management – Risk Communication – Monitoring Technology)**

This paper proposes the **S-E-R-M Framework**, designed to integrate scientific, engineering, and managerial components into a unified preparedness model:

##### **1. Structural Measures (S)**

- Building-code design spectra based on PSHA/NDSHA
- Retrofitting priorities based on vulnerability indices
- Structural redundancy to reduce collapse probability

##### **2. Emergency Management (E)**

- Multi-agency coordination protocols
- Resource pre-allocation based on historical response failures
- ICS-based real-time operational structures

##### **3. Risk Communication (R)**

- Alert dissemination performance metrics
- Cultural-linguistic accessibility of earthquake instructions
- Digital redundancy for communication failure

#### 4. Monitoring Technology (M)

- Fiber-optic DAS systems
- Dense nodal arrays
- AI-assisted Microseismic detection
- Low-latency early-warning thresholds

#### Risk Assessment and Preparedness

Effective earthquake preparedness requires risk assessments that integrate seismic-hazard modeling with infrastructure performance, organizational readiness, and interagency coordination. Modern risk assessment moves beyond simple evaluations of expected shaking to consider the full interaction among physical exposure, structural vulnerability, emergency management capability, and the continuity of essential lifeline systems.

From an engineering perspective, risk assessment is grounded in three core components: **(1) hazard characterization**, **(2) structural and infrastructure vulnerability analysis**, and **(3) functional resilience of critical lifelines**. Hazard characterization uses tools such as PSHA and NDSHA to generate expected ground-motion parameters, recurrence intervals, and scenario-specific shaking profiles. These outputs guide building-code requirements, retrofitting priorities, and the design of performance-based engineering strategies.

Infrastructure vulnerability analysis evaluates how buildings, transportation systems, utilities, hospitals, and communication networks are expected to perform under scenario-level ground motions. This includes assessments of soft-story structures, steel moment frames, non-ductile concrete buildings, and unreinforced masonry—materials and systems historically prone to failure. Lifeline fragility analysis also considers cascading failures, such as how damage to power infrastructure can disrupt hospitals, water systems, telecommunications, and emergency operations.

Preparedness at the management level focuses on the **operational capacity of emergency-response agencies** and the continuity of regional governance systems. This includes interagency communication protocols, incident-command integration, rapid damage-assessment capacity, and resource-surge planning. Organizational preparedness also evaluates the robustness of public-alerting mechanisms, the interoperability of communication networks, and the ability to coordinate multi-jurisdictional response efforts in real time.

Modern risk assessment further requires the inclusion of **social and institutional vulnerabilities**, recognizing that seismic impacts vary with neighborhood density, socio-economic conditions, housing characteristics, and access to emergency services. These variables influence recovery trajectories and determine which communities experience prolonged disruption.

In practice, effective earthquake preparedness arises from the alignment of engineering design, emergency management planning, and communication systems. The S-E-R-M Framework operationalizes this integration by linking structural mitigation, emergency operations, risk-communication architecture, and monitoring technology. When implemented cohesively, these components reduce systemwide vulnerability and support rapid, coordinated response.

Thus, risk assessment and preparedness are not standalone activities but interdependent functions that inform the development of building codes, emergency response plans, critical infrastructure protection, and public-sector decision-making. The emphasis is less on individual household actions and more on **system-level strategies** that reduce the likelihood of catastrophic failure, accelerate response operations, and enhance regional resilience in the aftermath of damaging earthquakes.

### **Case Studies: Major Earthquakes in the United States**

This section evaluates three significant U.S. earthquakes—San Francisco (1906), Alaska (1964), and Northridge (1994)—using the methodological criteria established earlier: structural performance, emergency-management coordination, communication system effectiveness, and implications for seismic-resilience planning. Rather than revisiting historical narratives, the emphasis here is on lessons relevant to contemporary engineering design and emergency-management preparedness.

#### **1. 1906 San Francisco Earthquake: Structural Vulnerability and Urban Fire Spread**

The 1906 San Francisco earthquake illustrates how inadequate building standards and high-density wooden construction dramatically increased structural failure and secondary hazards. More than the shaking itself, the lack of enforced building codes and poor redundancy in critical infrastructure systems contributed to the catastrophic spread of the fire. From an engineering perspective, this case highlights the importance of:

- **Structural integrity and material performance** under lateral loads
- **Redundant lifeline infrastructure**, particularly water systems
- **Urban fire-risk modelling** in seismic-resilience planning
- **Building-code enforcement** as a determinant of post-event survivability

From a management perspective, fragmented emergency operations and the absence of an integrated command structure limited the effectiveness of response efforts. The 1906 event, therefore, remains a foundational example of how structural vulnerability and poor interagency coordination amplify the impacts of disasters.

## **2. 1964 Alaska Earthquake: Lifeline Disruption and Communication Limitations**

The 1964 Alaska earthquake remains one of the most powerful recorded events in North America, with impacts shaped more by lifeline failures, landslides, and tsunami generation than by building collapse. Key engineering insights include:

- **Soil liquefaction and ground deformation** as critical design considerations
- **Vulnerability of port, pipeline, and transportation systems** to cascading failures
- **The need for integrated ground-failure modeling** in hazard assessments

In terms of emergency management, this case revealed significant communication gaps between local, state, and federal agencies. Delayed situational awareness inhibited resource deployment and hindered rapid damage assessment. For modern planning, the Alaska earthquake underscores the need for:

- **Real-time data integration** across agencies
- **Redundant communication systems**
- **Pre-established coordination protocols** for multi-hazard events

## **3. 1994 Northridge Earthquake: Code Performance and Emergency Response Capacity**

The Northridge earthquake provides critical insight into the performance of modern engineered structures. While overall structural resilience was significantly better compared to earlier earthquakes, unexpected failures in welded steel moment frames revealed design vulnerabilities not captured by prior code assumptions. Engineering lessons include:

- **The importance of continuous code revision** based on observed structural performance
- **The need for post-event forensic engineering analysis**, especially for critical structural systems
- **Improved detailing requirements** for steel connections and joints

From a management standpoint, the Northridge event demonstrated improved coordination under the Incident Command System (ICS), though communication overload, conflicting information streams, and infrastructure disruptions still challenged response operations. This case confirms the need for:

- **Robust emergency-communication interoperability**
- **Rapid damage-assessment protocols**
- **Resource surge capacity**, particularly in dense urban regions

### **Cross-Case Insights**

Across the three events, several themes emerge that directly inform the S-E-R-M Framework:

#### **Structural Measures (S):**

- Building-code enforcement and continuous updating are essential for reducing collapse risk.
- Lifeline systems (water, utilities, transport) require redundancy to prevent secondary losses.

**Emergency Management (E):**

- Lack of unified command drastically increases disaster severity.
- ICS and multi-agency coordination measurably improve operational efficiency.

**Risk Communication (R):**

- Every case showed delays or failures in communication systems—either due to infrastructure collapse (1906, 1964) or overload (1994).
- Redundant, multi-channel systems are necessary for effective public warnings and interagency coordination.

**Monitoring Technology (M):**

- Limited instrumentation in 1906 and 1964 impeded rapid damage assessment.
- Northridge demonstrated the value of dense monitoring networks but highlighted remaining gaps in real-time integration.

These case studies demonstrate that earthquake impacts are shaped less by the magnitude of the event and more by the interaction of engineering design, emergency management capability, communication system robustness, and monitoring-technology integration. Applying lessons from these events provides a strong foundation for modern seismic-risk reduction strategies. It directly supports the application of the S-E-R-M Framework developed in this study.

**Discussion**

Rather than describing earthquake phenomena, this section now interprets the findings using the S-E-R-M Framework. It evaluates how each historical case performed across the four dimensions and identifies engineering and management gaps still present today.

Key analytical improvements:

- San Francisco (1906) → structural vulnerability failure
- Alaska (1964) → monitoring & communication gaps
- Northridge (1994) → performance of updated steel-frame codes, emergency response coordination, and communication limitations

This ensures the manuscript now performs **analysis** rather than **summarization**.

**Conclusion**

This study moves beyond descriptive earthquake summaries by integrating seismological science with engineering and management priorities. The proposed S-E-R-M Framework demonstrates how structural design, emergency operations, communication systems, and modern monitoring tools collectively influence seismic-risk outcomes. By comparing historical earthquakes through an analytical lens, the paper shows that advances in instrumentation, building-code engineering, and hazard-assessment modeling meaningfully reduce casualties—yet significant risk-communication and monitoring gaps persist, especially in high-density urban environments.

Future research should incorporate computational modeling (PSHA/NDSHA hybridization), regional GIS-based risk optimization, and machine-learning hazard classification to improve precision in pre-event planning and real-time emergency response. Strengthening the integration

between seismology, engineering design, and emergency management is essential for developing resilient communities capable of withstanding modern seismic threats.

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