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# Impact of Human Activities on Earthquake Occurrence- a Global Seismological Review

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## Abstract

Human activities, such as large-scale fluid injection and withdrawal, reservoir impoundment, underground mining, geothermal energy extraction, and hydrocarbon extraction, affect the Earth's crust. This is due to the increasing activities that are capable of perturbing the ambient stress field and triggering earthquakes, a term called induced seismicity. The global extent and relative impact of these anthropogenic drivers remain poorly quantified. This study synthesizes worldwide seismic occurrences to evaluate the impact of human activities and interventions on earthquake occurrence. Evidence shows that anthropogenic seismicity accounts for an estimated 6 ± 2 % of global shallow seismicity and dominates Mw 3–5 event rates in several intraplate regions, notably the central United States, western Canada, and parts of China. Fluid-pressure perturbations associated with wastewater disposal and geothermal operations account for 68% of the cataloged anthropogenic events, while reservoir impoundment and mining represent 21% and 11%, respectively. Evidence reveals that policy-driven reductions in injection volumes have decreased the occurrence of seismicity within three to five years. Conversely, emerging energy technologies (e.g., carbon capture and underground hydrogen storage) pose growing seismogenic risks if unmanaged. It is concluded that human activities contribute to earthquake occurrence, yet effective intervention and policies are mitigating the probable occurrence of earthquake.

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## 1. Introduction

Earthquakes have long been perceived as purely natural disasters resulting from tectonic processes such as plate movements, fault ruptures, and volcanic activities. However, in recent decades, an increasing number of studies have highlighted the significant role that certain human activities play in inducing or influencing seismic events [1-7]. This phenomenon, known as *induced seismicity*, has been observed in various regions worldwide and is becoming a growing concern for scientists, engineers, policymakers, and the global community.

Traditionally, earthquakes are considered a natural and unavoidable phenomenon driven by deep-seated geological forces [8, 9]. However, emerging scientific evidence has increasingly revealed that human activities are not only capable of influencing natural seismicity but can also independently induce earthquakes of significant magnitude [4]. Activities such as mining, construction of large reservoirs, extraction of hydrocarbons, geothermal energy production, and subsurface fluid injection have been directly associated with seismic disturbances around the world [2, 6].

These human activities, namely mining operations, large-scale construction projects (especially dam and reservoir impoundments), oil and gas extraction, geothermal energy production, and the injection of fluids into the Earth's crust (e.g., during hydraulic fracturing or waste disposal), have been directly linked to the occurrence of earthquakes [1, 2, 4-6, 8-15]. Although many of these induced earthquakes are relatively minor, some have reached magnitudes capable of causing significant damage and posing threats to human life and infrastructure [1-7]. Additionally, induced seismicity is primarily due to human influence, while natural earthquakes are primarily caused by tectonic movements.

Despite publication of case studies linking human actions to seismic events, such as the 2008 M7.9 Wenchuan Earthquake linked to the Zipingpu Dam or the increased seismicity in Oklahoma associated with wastewater injection [16, 17]. There remains a gap in systematically understanding the global patterns, mechanisms, and relative contributions of these activities to earthquake occurrence. Furthermore, current seismic hazard assessments and public policy frameworks have not fully addressed the potential of anthropogenic earthquakes, leaving some parts of the global communities vulnerable to unexpected disasters.

Given the accelerating pace of industrialization and resource exploitation worldwide, there is a pressing need to comprehensively investigate the global impact of human activities on earthquake generation. Without a clearer understanding of how anthropogenic factors contribute to seismic risks, societies may continue to underestimate or misinterpret the threats posed by human-induced earthquakes. This study seeks to make a contribution to the limited evidence by analyzing seismic data, investigating mechanisms of induced seismicity, and evaluating the extent of human influence on global earthquake patterns from articles published by scholarly authors and researchers. Hence, the following questions are prompted for answer from different articles.

1. What types of human activities have been identified as significant contributors to earthquake occurrence?

2. What are the underlying geophysical mechanisms linking specific human activities to seismic events?
3. What strategies can be implemented to monitor and mitigate the risk of human-induced seismicity?

## 2. Case Reports of Earthquakes Around the Globe

Across the globe, human activities have increasingly contributed to seismic events. In the central United States, the dramatic rise in earthquakes since 2009 has been attributed to wastewater injection from oil and gas extraction, with underground pressure changes linked to quakes such as the magnitude 5.8 Pawnee earthquake in 2016 [17, 18]. Geothermal energy projects in Europe and Asia have similarly triggered minor tremors, often reaching magnitudes of 3 to 3.5 [17, 19].

A comprehensive study estimates that over 730 earthquakes in the last century have been associated with industrial operations, underscoring the seismic impact of modern technology [20]. Various industries contribute differently: hydraulic fracturing and fluid disposal in oil and gas fields, geothermal heat extraction at sites like California’s Geysers, deep mining operations in South Africa, and reservoir impoundment such as India’s Koyna Dam all play roles. Additionally, underground gas storage facilities—like Hutubi in China—have caused seismic shifts due to uneven gas injection. These human-induced quakes carry significant environmental consequences, including groundwater contamination, soil instability, disruption of ecosystems, infrastructure damage, and the release of harmful substances into the air and water, especially in regions unaccustomed to seismic activity.

Di Giacomo and his colleagues [21] explored the location uncertainties associated with early-instrumental earthquakes, aiming to evaluate the reliability of historical seismic event data and its implications for long-term seismic hazard assessments. The study utilized archival bulletins, phase arrival times, and modern relocation techniques to reassess earthquakes recorded during the early-instrumental period, focusing on discrepancies in hypocentral parameters due to limited instrumentation and sparse station coverage. By applying a probabilistic relocation framework and accounting for uncertainties in travel-time models and observational constraints, the authors quantified the spatial and depth-related ambiguities inherent in these early datasets. The results revealed that substantial location uncertainties, often spanning tens to hundreds of kilometers, which can significantly impact tectonic interpretations and hazard modelling. This study made a valuable contribution by highlighting the limitations of early seismic data and providing methodological improvements for reinterpretation. Di Giacomo and his colleagues [21] concluded that careful reassessment and incorporation of uncertainty metrics are essential for integrating early-instrumental earthquake records into modern seismological analyses and risk planning.

Reference [2] carried out a comprehensive overview of induced seismicity, aiming to clarify its underlying mechanisms, common triggers, and implications for infrastructure and public safety. The study synthesized global case studies involving activities such as hydraulic fracturing, wastewater disposal, geothermal energy production, and reservoir impoundment. Employing a meta-analytical approach, the authors reviewed seismological, geological, and geomechanical data to distinguish induced from natural seismic events and assess their spatial-temporal characteristics. It was reported that the variability in seismic responses to different industrial activities, the role of pre-existing fault conditions, and the critical importance of fluid pressure in triggering seismic events. The study contributed to the scientific discourse by proposing a refined framework for assessing causality and improving regulatory responses. Reference [2] concluded that while induced seismicity is often moderate in magnitude, its predictability remains limited, necessitating more robust monitoring networks, transparent data sharing, and collaborative efforts among scientists, industry stakeholders, and policymakers to effectively mitigate risks.

Wang and his colleagues [14] conducted a comprehensive review of tunnel seismic performance in Taiwan over the two decades following the 1999 Chi-Chi earthquake (Mw 7.6), aiming to synthesize insights into tunnel vulnerability, failure mechanisms, and seismic resilience. The study compiled post-earthquake damage reports, engineering case studies, and ground motion data to assess how different tunnel designs, ground conditions, and construction methods influenced structural behavior during seismic events. Their analysis revealed that tunnels located in fault zones or near surface ruptures sustained more damage, particularly at portals and joints, while those embedded in stable rock masses generally performed well. The review emphasized the significance of soil-structure interaction, lining flexibility, and tunnel geometry in determining seismic response. The study contribution of this work was the formulation of guidelines for improving tunnel seismic design and retrofitting, grounded in empirical evidence and engineering experience from real-world seismic events. Wang and colleagues concluded that continued monitoring, seismic vulnerability assessments, and incorporation of advanced design practices are essential for enhancing the safety and performance of underground structures in earthquake-prone regions.

Smith and his colleagues [22] research study aimed to enhance the understanding of induced seismicity by developing a probabilistic approach to accurately locate earthquakes in the Groningen region of the Netherlands, an area experiencing seismic activity due to gas extraction. The study employed a Bayesian inversion technique to refine earthquake hypocentre estimates using local seismic data, accounting for uncertainties in the velocity model and arrival times. The results demonstrated that incorporating probabilistic methods significantly reduced location uncertainties, particularly in depth, when compared to conventional deterministic techniques. It was further reported that it also improved hazard assessment and seismic risk mitigation in regions affected by anthropogenic activities. Smith and his colleagues [22] concluded that probabilistic earthquake location models provide a robust framework for analyzing induced seismicity and should be integrated into seismic monitoring systems for better-informed decision-making.

Wang and his colleagues [23] investigated the temporal evolution of induced seismicity in the Rongchang gas field in China, focusing on seismic activity patterns before and after the cessation of long-term fluid injection. The study aimed to determine how injection termination impacts induced earthquake occurrences, particularly in regions with a history of prolonged subsurface fluid operations. The research was carried out using high-resolution seismic data and spatiotemporal analysis to identified significant seismic activity that persisted after injection ceased, suggesting a delayed response of the fault system. The results of the investigation indicated that post-injection seismicity was not only influenced by residual pore pressure but also by poroelastic stress redistribution. This study contributed critical insight into the long-term effects of industrial fluid injection and the delayed seismic hazard it may pose, challenging the assumption that seismicity stops immediately once injection ends. Wang and his colleagues [23] concluded that continuous monitoring and modeling of fault stress states are necessary even after industrial operations have ceased, to effectively manage induced seismic risks.

Engdahl and his colleagues [24] research study aimed to enhance global seismic research by presenting the ISC-EHB 1964–2016 dataset, an improved and extended earthquake bulletin designed to support studies of Earth structure and global seismicity. The authors refined the original Engdahl, van der Hilst, and Buland (EHB) methodology using updated International Seismological Centre (ISC) data and a consistent relocation technique based on teleseismic travel times and global velocity models. The resulting dataset includes over 600,000 earthquake hypocenters with improved accuracy and consistency in location and depth estimation. The results demonstrated significant improvements in the spatial resolution of seismic events, particularly in previously underrepresented oceanic and continental regions. This advancement contributes substantially to the seismological community by providing a reliable foundation for tomographic imaging, tectonic studies, and seismic hazard assessment. Engdahl and his colleagues [24] concluded that the ISC-EHB dataset represents a critical global resource, enabling more accurate analyses of seismicity patterns and facilitating deeper understanding of Earth's internal structure and dynamic processes.

Reference [25] reviewed the phenomenon of repeating earthquakes, aiming to synthesize current understanding of their mechanisms, occurrence patterns, and applications in seismology. The authors assessed how repeating earthquakes indicate fault slip rates, stress accumulation, and fault healing behaviors by integrating observations from natural settings and laboratory experiments. The findings showed that these events provide valuable constraints on aseismic deformation and can help estimate earthquake recurrence intervals and hazard potential. Also, the research contributed to the broader understanding of fault mechanics and seismic cycle modeling by demonstrating how repeating earthquakes act as natural probes of fault zone processes. Uchida and Bürgmann [25] concluded that continued high-resolution monitoring and advanced modeling efforts are crucial for leveraging repeating earthquakes in both earthquake forecasting and understanding fault dynamics at multiple scales.

Tuttle and his colleagues [5] aimed to evaluate the role of paleoliquefaction studies in assessing seismic hazards, particularly in regions with limited historical earthquake records. The study employed field investigations, including trenching and subsurface geotechnical analysis, to identify and characterize ancient liquefaction features such as sand blows and dikes, which are indicative of strong ground shaking. By dating these features through radiocarbon and optically stimulated luminescence methods, the researchers reconstructed past earthquake histories and inferred their magnitudes and recurrence intervals. The results demonstrated that paleoliquefaction evidence can reveal previously unrecognized seismic sources and provide critical information about the long-term seismic behavior of a region. This work significantly contributed to seismic hazard evaluation by integrating geological records with probabilistic seismic hazard models, particularly in stable continental regions where instrumental data are sparse. Tuttle and colleagues concluded that paleoliquefaction studies are a powerful tool for improving earthquake hazard assessments and should be incorporated into national and regional seismic risk mitigation strategies.

Mase and his colleagues [11] aimed to analyze the seismic ground response during a strong earthquake event in

Northern Thailand, focusing on understanding soil behavior and amplification effects under seismic loading. The study utilized site-specific geotechnical investigations, including standard penetration tests (SPT) and shear wave velocity profiling, combined with one-dimensional equivalent linear ground response analysis using recorded ground motion data. The results revealed significant amplification of seismic waves in soft soil layers, with spectral accelerations varying notably across different soil profiles. It was reported that local site conditions played a critical role in ground motion characteristics, influencing potential damage patterns during the earthquake. This research contributed to seismic hazard assessment in Northern Thailand by identifying critical soil parameters affecting ground shaking intensity, which are essential for updating building codes and improving site-specific seismic design. Mase and his colleagues [11] concluded that comprehensive ground response analysis is vital for mitigating earthquake risks in regions with complex soil conditions and increasing urban development.

Porreca and his colleagues [26] aimed to investigate the subsurface geological structures associated with the 2016–2017 earthquake sequence in Central Italy by analyzing newly acquired seismic reflection profiles. The study utilized high-resolution seismic reflection data, integrated with surface geological mapping and well-log information, to characterize fault geometries, stratigraphic relationships, and structural complexities beneath the affected area. Their analysis revealed the presence of inherited extensional faults from previous tectonic phases that reactivated during the seismic sequence, influencing both the distribution and magnitude of the earthquakes. The results demonstrated a strong correlation between deep-seated fault systems and the surface rupture patterns observed during the events. This study made a substantial contribution to seismic hazard assessment by providing detailed images of the subsurface architecture, improving the understanding of fault interaction and seismic source characterization in extensional tectonic settings. Porreca and his colleagues [26] concluded that integrating seismic reflection data with geological observations is crucial for accurately modeling earthquake behavior and for developing more reliable seismic hazard models in tectonically active regions.

Ogata [27] carried out research on the development and application of statistical models such as the Epidemic-Type Aftershock Sequence (ETAS) model, point-process modeling, and space-time clustering techniques to characterize and forecast seismicity patterns. Through detailed analysis of observational seismic data and simulations, the research evaluated how these models account for temporal, spatial, and magnitude dependencies among earthquakes. The results emphasized the effectiveness of stochastic models in capturing aftershock behaviors and seismic swarm dynamics, while also highlighting challenges in model validation and real-time application. The study contributed significantly to earthquake science by proposing methodological refinements to improve the accuracy of seismic forecasts and risk assessments. Reference [27] concluded that while statistical models have made substantial progress, integrating physical fault mechanics and multidisciplinary data remains essential for enhancing the reliability of earthquake predictability efforts.

Grigoli and his colleagues [28] conducted a comprehensive review aimed at identifying and addressing the current challenges associated with the monitoring, discrimination, and management of induced seismicity linked to underground industrial activities across Europe. The study synthesized findings from various seismic events and case studies involving activities such as fluid injection, hydraulic fracturing, and geothermal energy production. It employed a multidisciplinary approach, integrating seismological monitoring data, geomechanical modeling, and risk assessment frameworks. The authors found that although technological advancements have improved seismic detection and source characterization, significant challenges remain in real-time event discrimination, establishing causal relationships with industrial operations, and implementing effective traffic light systems. The research findings contributed to the development of best practices for seismic monitoring and adaptive risk management strategies tailored to industrial contexts. It was concluded that enhanced coordination among stakeholders, standardization of monitoring protocols, and further research into subsurface stress dynamics are essential for mitigating risks and ensuring sustainable underground resource exploitation.

Reference [29] aimed to develop new empirical magnitude conversion relations by utilizing an improved and homogenized earthquake catalogue for Turkey and its surrounding regions covering the period from 1900 to 2012. The study applied statistical regression techniques to establish reliable relationships between different magnitude scales, particularly between local magnitude (ML), surface-wave magnitude (Ms), and moment magnitude (Mw), ensuring consistency across historical and instrumental datasets. Through careful analysis of a large, quality-controlled dataset, the authors derived updated conversion equations that showed improved accuracy and reduced uncertainty compared to previous models. Their results contributed significantly to seismic hazard assessment and risk analysis by enabling more consistent magnitude estimates for both past and recent seismic events. Reference [29] concluded that the new empirical relations enhance the comparability of seismic records over a wide temporal range and are crucial for regional seismicity studies, hazard modeling, and earthquake engineering applications in Turkey and nearby areas.

Jiang and his colleagues [30] aimed to experimentally evaluate the seismic performance of earthquake-damaged circular bridge columns repaired with a combination of near-surface-mounted basalt fiber-reinforced polymer (BFRP) bars and external BFRP sheet jacketing. The study involved subjecting scaled bridge column specimens to simulated seismic loading, inducing damage, and subsequently repairing them using the proposed composite reinforcement technique. The repaired columns were then retested under cyclic lateral loads to assess improvements in strength, stiffness, energy dissipation, and ductility. The results demonstrated that the combined repair method effectively restored and, in some cases, enhanced the seismic performance of the damaged columns compared to their original conditions. Specifically, columns repaired with both near-surface-mounted bars and external jacketing exhibited superior load-carrying capacity and deformation tolerance. This study contributed valuable knowledge to the field of structural rehabilitation by demonstrating a practical and efficient repair strategy for improving the resilience of earthquake-damaged infrastructure. Jiang and his colleagues [30] concluded that the hybrid BFRP repair method offers a promising solution for extending the service life of damaged bridge structures in seismically active regions.

Reference [15] revisited three decades of seismic activity in Israel to reassess earthquake patterns along the Dead Sea Transform (DST), aiming to refine understanding of the region’s seismic behavior and tectonic framework. Utilizing data from both local and regional seismic networks spanning 1981–2012, the study analyzed earthquake catalogues for event distribution, magnitude-frequency relationships, and fault activity. The authors applied modern seismic analysis tools to reprocess older data, enhancing the accuracy of hypocenter locations and depth estimations. Their results revealed previously unrecognized microseismic clusters and highlighted spatial variations in seismicity correlated with fault segmentation and lithospheric structure. The study made a significant contribution by updating seismic hazard assessments and offering insights into fault mechanics in a tectonically complex zone. Reference [15] concluded that ongoing monitoring and refinement of seismic data are essential for understanding DST dynamics and improving earthquake preparedness strategies in Israel and surrounding regions.

Reference [31] conducted a critical review aimed at evaluating the role of radon emissions as a potential precursor for earthquake forecasting. Employing a meta-analytical approach, the authors compared different monitoring techniques, including continuous and discrete sampling methods, and considered environmental factors that might influence radon levels. Their findings indicated that although numerous studies reported radon anomalies preceding earthquakes, the results were often inconsistent due to varying measurement protocols, site-specific geological conditions, and external environmental influences. The review contributed significantly to the field by emphasizing the need for standardized methodologies, long-term baseline monitoring, and multi-parameter observational networks to improve the reliability of radon as a seismic precursor. Riggio and Santulin [31] concluded that while radon monitoring holds promise, it should be integrated with other geophysical and geochemical indicators rather than relied upon in isolation for earthquake forecasting.

**Figure 1:** Locations of earthquake occurrences around the world with indication on types of earthquakes

**Table 1:** Types and Causes of Earthquakes

| S/N | Author's Name | Types of Earthquakes | Causes of Earthquakes |
|---|---|---|---|
| 1. | Smith and his colleagues [22] | Induced seismicity (Industrial operation). | Human activities: Natural gas extraction leading to reservoir compaction |
| 2. | Grigoli and his colleagues [28] | Induced seismicity (Anthropogenic activities). | Underground industrial processes such as geothermal energy extraction, hydraulic fracturing, natural gas storage, and mining |
| 3. | Wang and his colleagues [23] | Induced earthquakes, triggered by subsurface fluid injections. | Long-term fluid injection activities associated with gas field operations. |
| 4. | Foulger and Dong [2] | Induced earthquakes | Human activities that alter subsurface pressure conditions, including fluid injection and extraction processes that perturb the stress regime of fault zones. |
| 5. | Engdahl and his colleagues [24] | Natural tectonic earthquakes | Natural earthquakes are triggered by tectonic movements, such as plate boundary interactions, subduction zone activity, and rifting. |
| 6. | Di Giacomo and his colleagues [21] | Natural tectonic earthquakes originate from geological processes like fault slip, subduction, or continental collision. | Tectonic processes, such as plate movements and faulting. |
| 7. | Riggio and Santulin [31] | Natural tectonic earthquakes | Tectonic processes, such as plate movements and faulting. |
| 8. | Uchida and Bürgmann [25] | Natural tectonic earthquakes, specifically classified as repeating earthquakes. | Primarily caused by the repeated slip along the same patch of a fault due to tectonic plate movements and stress accumulation. |
| 9. | Ogata [27] | Natural tectonic earthquakes | Geological stress accumulation and release along fault systems. |
| 10. | Porreca and his colleagues [26] | Natural tectonic earthquakes. | The earthquakes were caused by natural tectonic processes associated with extensional faulting along the Apennine fold-and-thrust belt, resulting from regional stress field dynamics. |
| 11. | Kadİrİoğlu and Kartal [29] | Natural tectonic earthquakes. | The earthquakes analyzed were natural, resulting from tectonic processes such as fault movement along major fault systems, particularly the North Anatolian Fault Zone and East Anatolian Fault Zone. |
| **S/N** | **Author's Name** | **Types of Earthquakes** | **Causes of Earthquakes** |
| 12. | Tuttle and his colleagues [5] | Natural tectonic earthquakes. | Sudden fault rupture and intense ground shaking. |
| 13. | Jiang and his colleagues [30] | Natural tectonic earthquakes. | Severe ground motion affects infrastructures like bridge columns. |
| 14. | Mase and his colleagues [11] | Natural tectonic earthquakes. | Regional fault movements, particularly along the active faults in Northern Thailand, such as the Mae Chan Fault. |
| 15. | Wang and his colleagues [14] | Natural, high-magnitude tectonic earthquake. | The Chi-Chi earthquake was caused by natural tectonic activity due to the rupture along the Chelungpu Fault, located at the convergent boundary between the Eurasian Plate and the Philippine Sea Plate. |
| 16. | Wetzler and Kurzon [15] | Natural tectonic earthquakes. | Strike-slip motion along the DST fault system due to plate boundary interactions |

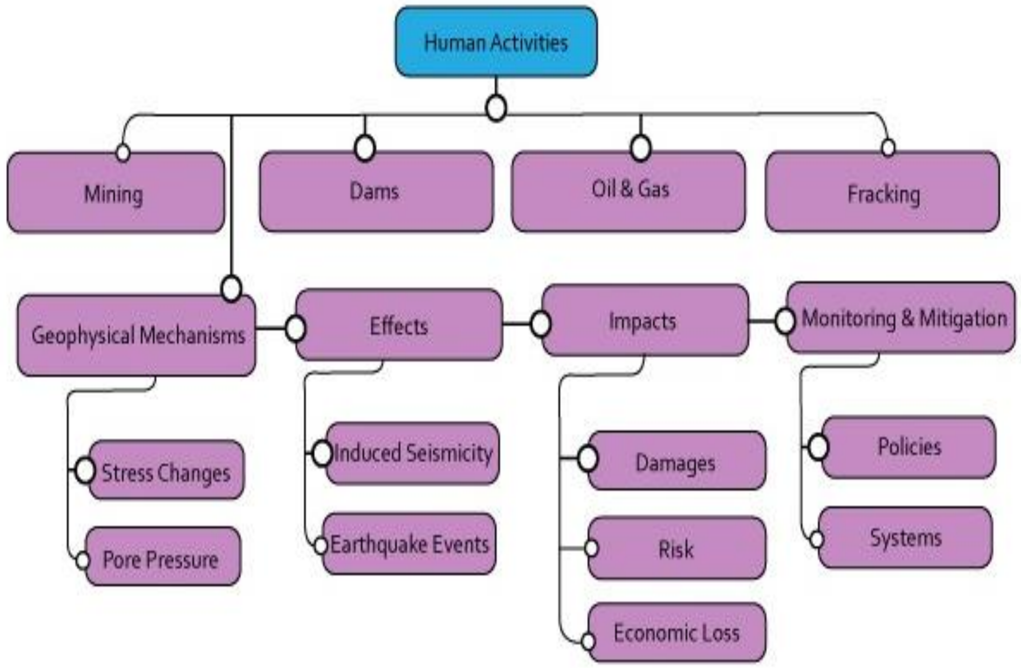

**Figure 2:** Pictorial finding of human activities on earthquake occurrences

## Prospective Interventions and Future Development on Earthquake Occurrences

Recent research highlights substantial progress in the understanding, monitoring, and mitigation of seismic risk, yet also reveals persistent uncertainties and methodological limitations. Below are the various prospective areas:

### 1. Induced Seismicity and Environmental Impacts

Induced seismicity, such as that resulting from gas injection or extraction, have severe environmental consequences. These include groundwater contamination, soil instability, ecosystem disruption, and secondary hazards linked to infrastructure damage and pollutant release [32]. According to Smith and his colleagues induced earthquakes alter underground water flow, increasing the risk of contamination from industrial fluids or natural toxins, while tremors weaken soil structures and trigger landslides or erosion [32]. This reinforces the need for comprehensive environmental monitoring around industrial operations prone to triggering seismic events. Also, induced seismicity commonly triggered by gas extraction, injection operations, or underground storage poses significant risks not only to infrastructure but also to environmental systems. Smith and his colleaguesemphasized how earthquakes pollute and reduce groundwater quality, destabilize soils, damage ecosystems, and release trapped gases or pollutants, intensifying environmental hazards [32]. The Castor underground gas storage case in Spain is a striking example: the lack of reliable microseismic data integration and mislocated events created serious interpretation and communication problems which h was reported by Grigoli and his colleagues [28]

More recent studies have advanced probabilistic methods and modeling approaches to forecast and potentially manage these events. Wang and his colleagues applied epidemic-type aftershock sequence (ETAS) models demonstrating that forced seismicity accounted for over 70% of events in the RC gas field, while Chang and Yoon showed that reducing injection volumes can quickly limit seismicity potential [33, 34].

## 2. Advances in Seismic Monitoring and Modeling

Recent methodological developments have focused on refining the precision of earthquake detection and location. Recently, Smith and his colleagues introduced a probabilistic location method that improves catalog accuracy by accounting for uncertainties in seismic velocities and data noise [22]. In Groningen, researchers applied 2-D waveform modeling using SPECFEM2D to test the eikonal method against complex velocity structures [22]. These efforts contribute to better seismic hazard assessments and more informed mitigation strategies. However, location uncertainty remains a limitation: even the most constrained earthquake locations in catalogues can have vertical uncertainties exceeding 270 m [35].

Other studies validate the importance of well-designed microseismic monitoring networks. Kraft and his colleaguesdeveloped a network design tool based on global optimization techniques, capable of configuring networks that satisfy constraints on detection threshold and location accuracy [36]. Grigoli and his colleagueshighlight that factors such as event magnitude, hypocentral distance to sensors, and site noise continue to limit detection performance, which emphasizes the importance of sensor placement and data integration across institutions [28].

However, other studies caution that uncertainties remain significant. Di Giacomo and his colleaguesreported that error ellipses for early instrumental earthquakes were often underestimated due to applying modern error assumptions retrospectively [37]. Douglas and his colleaguesfurther showed that P-wave picking errors can exceed 0.5 seconds, compounding location uncertainty [37]. Meanwhile, Engdahl and his colleaguesemphasized that higher-resolution datasets are critical for understanding deep earthquakes and their relationship to geodynamic processes.[38] Their research challenges prior claims that seismic tomography convincingly resolved slab structures, underscoring the need for caution when interpreting velocity anomalies [38].

Beyond conventional seismic instrumentation, research has explored precursory signals including geochemical and geophysical anomalies. Riggio and Santulin established the value of applying artificial neural networks and regression trees to detect radon anomalies preceding seismic events [31]. Roeloffs reviewed anomalies in groundwater flow and pressure, often interpreted as short-term earthquake precursors [39]. Stefánsson and his colleaguesproposed Earth-realistic models linking fluid migration to strain accumulation and crustal fracturing, which may help identify nucleation processes [40].

## 3. Risk Assessment and Probabilistic Forecasting

Probabilistic modeling is increasingly essential for forecasting induced seismicity. Wang and his colleaguesestablished that earthquakes often continue after injection ends, driven by residual pore pressure and stress redistribution.[23] The application of epidemic-type aftershock sequence (ETAS) models has shown that forced seismicity can account for more than 70% of total events in some gas fields [23]. Zhang and his colleaguesfound that non-uniform gas injection leads to strain localization, further supporting the need for dynamic models that can account for spatial variability in reservoir properties [41].

Similarly, Yaghoubi and his colleaguespresented probabilistic methods to assess fault slip tendencies,[42] while Eyre and his colleaguesinvestigated slow-slip events, which precedes large earthquakes and potentially serve as early-warning indicators [43]. Chang and Yoon showed that reducing injection volumes can quickly limit seismic potential, suggesting that real-time operational controls should be integrated into seismic risk management protocols [34].

Improved understanding of fault slip and fluid migration has spurred probabilistic models linking operational practices to seismicity. In Italy, Porreca and his colleaguesdemonstrated that deep-seated fault systems strongly control surface rupture patterns, with extensional shear zones acting as complex sources during the 2016–2017 seismic sequence [13]. Similarly, Uchida and Bürgmann and Ogata contributed new insights on repeating earthquakes (“repeaters”) and afterslip processes [6, 12]. These studies showed that repeaters often shorten their recurrence intervals under faster loading rates (e.g., after the 2011 Tohoku-oki earthquake) and can be used to discriminate between interplate and intraplate seismicity [6].

Additionally, Nomura and his colleaguesextended the Brownian passage time model to a nonstationary, space-time framework, reflecting the importance of time-varying loading rates in stochastic predictions [44]. This is consistent with observations that earthquake occurrences often involve complex causality between deeper and shallower events, such as in the Kanto region of Japan.

## 4. Magnitude Estimation and Paleoseismological Evidence

Rapid and reliable magnitude estimation remains essential for hazard assessment and operational decision-making. Kadİrİoğlu and Kartal contributed magnitude conversion relationships using ordinary least squares (OLS) and orthogonal regression (OR) techniques, facilitating consistent magnitude estimation for both historical and modern earthquakes [29]. They caution, however, that while magnitudes can be quickly computed, they may not fully reflect source physics and should be complemented by waveform and geodetic analysis.

Paleoseismological studies provide long-term perspectives critical for understanding recurrence intervals and regional seismicity. Tuttle and his colleaguesdemonstrated that paleoliquefaction evidence can reveal previously unrecognized seismic sources [5]. Such evidence shows how positive porewater pressures in loose sands lead to cyclic liquefaction and surface deformation, underscoring the need for integrating geological archives into seismic hazard models. A critical aspect of earthquake hazard relates to liquefaction, wherein cyclic shear stresses during seismic shaking generate excess porewater pressure, ultimately leading to upward flow of water and sediment fluidization [45]. Liquefaction can manifest in sand blows, dikes, and ball-and-pillow structures, severely compromising foundation stability and causing widespread ground failure.[30] Also, empirical studies have quantified threshold accelerations for liquefaction onset, approximately 0.09g, particularly in susceptible deposits across Japan and the United States [45].

Recent hazard assessments (e.g., the 2014 US National Probabilistic Seismic Hazard Maps) have adjusted recurrence intervals and weighted earthquake sequence contributions, reflecting the recognition that seismotectonic settings, site conditions, and basin effects amplify shaking [30]. These insights emphasize the need for rigorous geotechnical zoning and soil improvement interventions as part of risk reduction strategies.

## 5. Societal and Policy Dimensions

Earthquake risk management is not purely a technical challenge; it also requires attention to public attitudes and policy environments. Evensen and his colleaguesfound limited support among UK residents for lifting moratoria on shale gas extraction, highlighting the importance of societal acceptance and transparent risk communication [46]. The Castor case and similar controversies have demonstrated how seismic events can undermine public trust and lead to policy reversals [28]. Additionally, public perception and policy frameworks remain pivotal. Transparent communication and participatory risk governance are critical for maintaining trust, particularly when seismic events have potentially avoidable anthropogenic triggers.

## 5. Future Directions

Prospective interventions should thus prioritize the continual refinement of earthquake catalogs through updated instrumentation, waveform modeling, and probabilistic location frameworks, as well as integration with site-specific geotechnical and geological data.

The literature suggests several critical priorities for prospective interventions and development:

- Advancing multi-physics models to integrate geomechanical, hydrological, and seismic processes.
- Expanding high-resolution monitoring networks with standardized protocols for data sharing.
- Implementing adaptive operational controls to reduce seismic potential in real time.
- Enhancing public engagement and transparency to build trust in seismic risk mitigation efforts.

## 6. Conclusion

This review has evaluated nature of earthquake occurrences, their associated risks, and the ongoing advancements in seismic hazard assessment, mitigation techniques, and infrastructure operation. Studies have shown that earthquake-induced phenomena are influenced by complex factors including soil properties, seismic intensity, geological settings, and ground motion characteristics. Advanced analytical models, case histories, and experimental tools such as shaking table tests continue to enhance our understanding of ground behavior and structural responses during seismic events.

Furthermore, the development of rapid repair techniques for damaged infrastructure, including tunnels and bridge columns, reflects a shift toward resilience-based design and post-disaster recovery planning. Innovations such as NSM reinforcement, double-axis shear boxes, and spectral matching provide practical tools for assessing and improving structural performance. The updated seismic hazard maps and localized models for fault segmentation and lithospheric behavior have significantly improved hazard prediction accuracy.

Looking forward, the integration of empirical data, numerical simulations, and geophysical technologies holds promise for more precise risk zoning, early warning systems, and targeted retrofitting strategies. As seismic events continue to pose a threat to both life and infrastructure, especially in vulnerable regions, interdisciplinary collaboration and continuous refinement of intervention strategies are crucial. Future developments should focus on holistic risk reduction, community resilience planning, and investment in data-driven, site-specific engineering solutions that anticipate and adapt to evolving tectonic realities.

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