Seismic Resilience for Commercial Construction

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Table of Contents

- **Introduction**

Introduction

Commercial buildings are the backbone of modern communities. When earthquakes or other extreme loads strike, the ability of these facilities to protect life, limit damage, and return to service quickly determines not only the fate of a single project but the continuity of entire neighborhoods and regional economies. This book, Seismic Resilience for Commercial Construction, focuses on practical, design-to-build strategies that elevate performance well beyond minimum compliance. Our aim is to translate the best of structural engineering research and field experience into decisions that owners, engineers, and contractors can apply with confidence.

Resilience begins with clarity about performance. Life safety is essential, but for many commercial occupancies it is not sufficient. Hospitals, data centers, logistics hubs, retail centers, and office towers carry different expectations for downtime, repairability, and operational continuity. Throughout this book we frame choices in terms of resilience metrics—functional recovery time, allowable damage states, and lifecycle impacts—so project teams can align technical solutions with business objectives and community needs.

Achieving those outcomes requires an integrated toolkit. We examine structural systems and detailing for ductility and robust load paths; base isolation and supplemental damping to control demands; and retrofit strategies that elevate older buildings to modern performance targets. Equal attention is given to nonstructural components—mechanical, electrical, architectural, and facade systems—because in past events these have often driven downtime and losses even when primary frames performed adequately. For multi-story and industrial buildings, we address long spans, heavy equipment anchorage, cranes, mezzanines, and sensitive process lines where tolerances and vibration criteria intersect with seismic demands.

Constructability is treated as a core design parameter, not an afterthought. Sequencing, tolerances, connection access, prefabrication, and quality control can make or break the performance promised on paper. We highlight common pitfalls seen in post-event assessments—improper diaphragm collectors, inadequate anchorage of heavy nonstructural components, and missed load-path transitions—and show how early coordination and clear details prevent them. The chapters on procurement and contracts explore how delivery models, specifications, and risk allocation can either incentivize or impede resilient outcomes.

Resilience also extends beyond the ribbon-cutting. Owners and operators need plans for inspection, rapid assessment, and prioritized repairs; for maintaining spare parts and vendor agreements; and for integrating building performance with business continuity strategies. We include guidance on commissioning for seismic systems, monitoring options, and how to stage re-occupancy decisions safely. Case studies at the end of the book demonstrate what worked, what failed, and why—distilling lessons from recent earthquakes and extreme load events into replicable practices.

This is a practical book. Each chapter pairs concepts with checklists, decision frameworks, and constructible details aimed at helping teams make smart tradeoffs under budget and schedule constraints. Whether you are selecting between moment

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frames and braced frames, deciding if base isolation pencils out, planning a phased retrofit in an occupied facility, or mapping a recovery timeline that keeps tenants and operations viable, our goal is to meet you at the point where decisions get made—and to equip you to make them well.

CHAPTER ONE: The Seismic Hazard Landscape for Commercial Real Estate

Every commercial building begins its life as a bet against the ground beneath it. The bet may be calculated or casual, informed or wishful, but it is always there. Engineers pore over seismic hazard maps, geologists study fault scarps, and developers glance at building department checklists. Each brings a different lens to the same question: how hard might the earth shake here, and how much should we care? Understanding the hazard landscape is not just an academic exercise or a box to check on a permit application. It is the foundation for every decision that follows in design, construction, and long-term operations. A building in downtown Memphis faces a fundamentally different seismic reality than one in downtown San Francisco, and treating those realities as equivalent is the surest path to unpleasant surprises.

Seismic hazard, in the engineering sense, is not the same as earthquake risk, though the two terms often get tangled in conversation. Hazard describes what the ground might do, independent of what sits on top of it. It is a statement about the likelihood of certain levels of shaking at a given location over a specified time horizon. Risk, by contrast, folds in the vulnerability of the structure and the value of what is at stake. A modest warehouse in a high-hazard zone may have low risk if the contents are easily replaceable and the building is cheap to rebuild. A hospital in a moderate-hazard zone may carry enormous risk because downtime is measured in lives and millions of dollars per day. For commercial real estate, the distinction matters. Owners and investors think in terms of risk, but engineers can only manage risk if they start with an honest picture of the hazard. This chapter is about that picture.

The modern understanding of seismic hazard in the United States rests on a framework called probabilistic seismic hazard analysis, or PSHA. Developed in the 1960s and refined steadily since, PSHA combines what we know about where faults are, how often they rupture, how big those ruptures can get, and how shaking attenuates with distance into a single mathematical statement: the probability that a given level of ground motion will be exceeded at a site within a given time period. The framework is not perfect, and it has been the subject of spirited debate among seismologists for decades, but it remains the best tool available for translating geological uncertainty into engineering numbers. Every major building code in the

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country leans on PSHA results, and those results ultimately flow into the design accelerations that appear on a project's geotechnical report.

At the national scale, the United States Geological Survey publishes seismic hazard maps that most engineers encounter first. These maps display the spectral acceleration values, typically at periods of 0.2 seconds and 1.0 seconds, for a two-percent probability of exceedance in fifty years. That last phrase deserves unpacking. A two-percent probability of exceedance in fifty years roughly corresponds to a 1-in-2,500-year event on any given year, though it is not quite the same thing because the calculation accounts for the cumulative probability over the full fifty-year window. Practically, this is the level of shaking that the building code targets for new construction, and it is the number that shows up in design software, stamped drawings, and municipal review checklists. For anyone owning, developing, or financing commercial real estate, it is worth understanding that these maps represent an average over broad regions and may significantly understate or overstate the hazard for a particular site. They are a starting point, not a finish line.

Why might the maps understate local hazard? In some regions, the story goes well beyond what the color-coded contours suggest. The New Madrid Seismic Zone in the central United States is a textbook example. The zone produced a series of massive earthquakes in the winter of 1811 and 1812 that rang church bells in Charleston, South Carolina, and briefly reversed the flow of the Mississippi River. Instrumental recordings did not exist at the time, so seismologists must reconstruct the event from historical accounts, geological evidence, and physical models. The result is a zone of elevated hazard that covers parts of Missouri, Arkansas, Tennessee, Kentucky, and Illinois, yet many communities within it have building stocks that were designed and constructed with little thought to earthquakes. A commercial building in Memphis, for instance, may be governed by a building code that assigns relatively modest design forces, yet paleoseismological studies of the New Madrid zone suggest recurrence intervals for major events that are shorter than many people assume. The hazard is real, and the gap between perceived and actual risk is where buildings fail and businesses suffer.

California, by contrast, presents a different challenge: not underappreciation but complexity. The state sits astride dozens of active fault systems, from the San Andreas to the Hayward, the Imperial, and the lesser-known but equally dangerous faults that thread through the Los Angeles basin and the San Francisco Bay Area. Each fault has its own geometry, slip rate, and rupture behavior, and the interactions among them can produce shaking patterns that vary dramatically over short distances. A building on one side of a hill may experience significantly different ground motions than a building on the other side, even if both are nominally in the same seismic design category. Site effects, where soft soils amplify certain frequencies of shaking, can turn a moderate regional earthquake into a severe local event. The 1989 Loma Prieta earthquake demonstrated this vividly in the Marina District of San Francisco, where

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loose fill soils amplified shaking and caused widespread collapse of buildings that might have performed adequately on firmer ground.

The Pacific Northwest adds yet another flavor of hazard. The Cascadia Subduction Zone, stretching from northern California to Vancouver Island, is capable of producing magnitude nine earthquakes with rupture lengths exceeding a thousand kilometers. These events are rare by human standards, recurring every few hundred years on average, but their footprint of shaking is enormous. Cities like Portland and Seattle sit within the influence zone, and the shaking from a full subduction rupture will be long in duration and rich in low-frequency energy, a combination that poses particular challenges for tall commercial buildings and long-span industrial structures. The last major Cascadia event occurred in January 1700, identified through a combination of Japanese tsunami records and coastal marsh stratigraphy, which places the current moment somewhere in the zone of recurrence uncertainty. For commercial real estate owners with long hold periods, this is not a theoretical concern.

Moving beyond the continental United States, international contexts add further dimensions. Japan has arguably the most sophisticated seismic hazard assessment infrastructure in the world, born of necessity in a country that experiences thousands of felt earthquakes each year. New Zealand, Chile, and Turkey have each produced devastating earthquakes in recent decades that have reshaped their respective building codes and, in some cases, entire approaches to commercial construction. For firms with international portfolios or projects, understanding that seismic hazard frameworks vary in maturity, methodology, and underlying data quality is essential. A design ground motion derived from a well-populated seismological network in Japan will carry far more confidence than one estimated for a rapidly growing city in a developing seismic zone where instrumental records are sparse and paleoseismic data is limited.

What does all of this mean for the commercial real estate stakeholder who is not a seismologist? It means asking the right questions early. When a site is under consideration, the geotechnical investigation should not simply produce boring logs and bearing capacity numbers. It should include a site-specific seismic hazard assessment, or at minimum a critical review of the default hazard values from the national maps, especially for high-value or mission-critical facilities. The geotechnical engineer should characterize the site class according to the code's soil profile categories, identify any potential for liquefaction or landslides, and flag proximity to known fault traces. None of this is exotic, but it is frequently skipped or downgraded in an effort to control costs on due diligence phases. The irony, of course, is that a small investment in understanding the hazard can prevent orders-of-magnitude larger losses after an event.

Engineers sometimes talk about the "level of shaking" as though it were a single number, but ground motion is richer and more complicated than that. The shaking

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during an earthquake is not a steady vibration. It arrives as a complex, irregular signal that varies in intensity and frequency content over the duration of the event. Engineers characterize this signal using several parameters, and each captures a different aspect of what the building will experience. Peak ground acceleration, or PGA, is the maximum acceleration of the ground during shaking, expressed as a fraction of gravitational acceleration. It is intuitive and widely reported, but it is an imperfect predictor of structural response because it says nothing about how long shaking persists or at what frequencies it concentrates. Spectral acceleration, the acceleration that a hypothetical single-degree-of-freedom oscillator with a given natural period would experience, is more useful for engineering because it directly maps to the dynamic characteristics of a building. Design response spectra, constructed from PSHA results and displayed as curves of spectral acceleration versus period, are the primary inputs to code-based seismic design.

The response spectrum deserves a bit more attention because it is the bridge between hazard science and structural engineering. A typical design spectrum will show a plateau in the short-period range, rising steeply from zero period to a peak value around 0.2 to 0.5 seconds, then declining at longer periods. The shape of this curve is dictated by the magnitude of the earthquake, the distance to the source, the site conditions, and the damping level assumed for the oscillator. Short, stiff structures respond to the left side of the curve, while tall, flexible structures respond to the right side. This is why two buildings on the same site, built to the same code, can experience very different demands during the same earthquake. The hazard, as expressed through the spectrum, speaks differently to different structures.

For commercial real estate, the implications are significant. A five-story office building with a fundamental period of roughly one second will draw its design forces from the middle of the spectrum, while a twenty-story tower with a period of three to four seconds will be governed by the long-period tail. In regions where subduction earthquakes dominate the hazard, such as the Pacific Northwest, the spectral values at long periods can be disproportionately high relative to short periods. This creates a design environment where tall buildings may face higher demands than shorter ones, reversing the intuition that bigger buildings are always more robust. Owners and developers of high-rise commercial properties should understand that their buildings may be more sensitive to hazard assumptions than their low-rise counterparts, and that site-specific studies become proportionally more important as height increases.

The concept of return period is another source of confusion worth addressing directly. Engineers speak of a 2,500-year earthquake, a 1,000-year event, or a 2,500-year mean return interval, and these numbers are often misinterpreted. A 2,500-year return period does not mean the event happens every 2,500 years on schedule. It means that in any given year, there is roughly a one-in-2,500 probability that the ground motion associated with that event will be exceeded. Over a fifty-year building life, the cumulative probability of exceedance works out to about two percent, which is

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the basis for the code's design-level hazard. Over a hundred-year period, the probability rises to nearly four percent. For commercial buildings that are designed to serve for many decades, and for investments that are evaluated over thirty- or fifty-year horizons, these probabilities are not negligible. They represent a meaningful chance of being hit, and they warrant serious consideration in portfolio risk management.

Recent years have also introduced a new dimension to hazard awareness in parts of the central and eastern United States: induced seismicity. Wastewater injection associated with oil and gas operations has been linked to increased rates of earthquakes in Oklahoma, Kansas, and parts of Texas. While most induced events have been moderate in magnitude, the frequency increase has been dramatic, transforming regions that were historically considered low hazard into areas with seismicity rates comparable to parts of California. Several moderate earthquakes in Oklahoma around 2016 drew national attention and prompted reevaluation of hazard models in the region. For commercial real estate in affected areas, this development underscores the importance of monitoring evolving hazard assessments rather than relying on historical seismicity alone. Hazard is not static, and the assumptions baked into older building evaluations may no longer reflect current reality.

The integration of hazard information into building codes follows a somewhat indirect path. National model codes, such as those published by the International Code Council and the American Society of Civil Engineers, adopt mapped hazard values and apply adjustment factors for site class, near-fault effects, and structural characteristics. The resulting design forces are intended to provide life safety under the design-level earthquake and collapse prevention under the maximum considered earthquake. For commercial buildings, the code's minimum requirements establish a baseline, but they do not automatically deliver the level of resilience that owners need. A building that meets minimum code requirements is designed to protect lives, not necessarily to remain operational, limit repair costs, or support business continuity. That distinction is at the heart of this book and will be explored in depth in the chapters that follow.

One of the emerging tools for going beyond code minimums is performance-based seismic design, or PBSD. Rather than designing to prescriptive force levels derived from simplified hazard inputs, PBSD starts with explicit performance objectives, such as immediate occupancy after a design-level earthquake or controlled damage with rapid repairability after a larger event. The process typically involves site-specific ground motion selection, response history analysis, and detailed evaluation of expected damage states across structural and nonstructural systems. PBSD is computationally more demanding and requires more sophisticated engineering than prescriptive design, but it allows the project team to align building performance directly with business and operational priorities. For high-value commercial assets, it increasingly represents the standard of care.

Owners and developers are sometimes surprised to learn that seismic hazard assessment is as much about uncertainty management as it is about obtaining a number. The PSHA framework was designed precisely to handle the fact that we cannot predict earthquakes, that our knowledge of fault behavior is incomplete, and that ground motion prediction equations carry significant variability. A hazard curve for a given site does not produce a single design value. It produces a distribution of possible ground motion levels, each associated with a probability. The code's design values represent points on that distribution, chosen to balance safety and cost. Understanding the width and shape of the underlying uncertainty distribution can inform decisions about whether to target performance above or near the code minimum. It can also illuminate how sensitive a building's performance will be to the inevitable gap between the assumed ground motion and whatever the earth actually delivers.

There is also a practical dimension to seismic hazard that is often overlooked in engineering discussions: insurance and financing. Commercial property insurers and lenders increasingly factor seismic risk into their underwriting and pricing decisions. In some regions, earthquake insurance is either unavailable or prohibitively expensive, reflecting a realistic assessment of the hazard. Properties in high-hazard zones, or those with known vulnerabilities such as soft-story configurations or unbraced masonry, may face higher premiums, difficulty obtaining coverage, or reduced borrowing terms. An owner who understands the hazard landscape and can demonstrate that the building has been designed and constructed with resilience in mind will have a material advantage in negotiations with insurers and lenders. The business case for seismic resilience, in other words, begins long before the first shovel breaks ground.

The seismic hazard landscape is not a fixed backdrop against which construction occurs. It evolves as new research refines our understanding of fault behavior, as instrumentation networks expand and improve, and as the built environment itself changes in ways that alter exposure. Sea-level rise, groundwater extraction, and large-scale subsurface activities can all modify the hazard picture over time. For commercial real estate, staying current with hazard assessments, maintaining awareness of emerging science, and building in the flexibility to adapt are not luxuries. They are the starting conditions for making sound investment and engineering decisions. The next chapter will take the hazard as described here and translate it into the performance targets and resilience metrics that guide the rest of the design and construction process. But first, the message of this chapter should be clear: the ground has a say in how a building performs, and listening to it carefully is the least expensive form of insurance a commercial project can buy.

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