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Gray swans: comparison of natural and financial hazard assessment and mitigation

Jerome L. Stein · Seth Stein

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Abstract Even advanced technological societies are vulnerable to natural disasters, such as the 2011 Tohoku earthquake and tsunami, and financial disasters, such as the 2008 collapse of the US housing and financial markets. Both resulted from unrecognized or underappreciated weaknesses in hazard assessment and mitigation policies. These policies relied on models that proved inadequate for reasons including inaccurate conceptualization of the problem, use of a too-short historic record, and neglect of interconnections. Japanese hazard models did not consider the possibility of multiple fault segments failing together, causing a much larger earthquake than anticipated, and neglected historical data for much larger tsunamis than planned for. Mitigation planning underestimated the vulnerability of nuclear power plants, due to a belief in nuclear safety. The US economic models did not consider the hazard that would result if many homeowners could not pay their mortgages, and assumed, based on a short history, that housing prices would keep rising faster than interest rates. They did not anticipate the vulnerability of the financial system to a drop in housing prices, due to belief that markets functioned best without government regulation. Preventing both types of disasters from recurring involves balancing the costs and benefits of mitigation policies. A crucial aspect of this balancing is that the benefits must be estimated using models with significant uncertainties to infer the probabilities of the future events, as we illustrate using a simple model for tsunami mitigation. Improving hazard models is important because overestimating or underestimating the hazard leads to too much or too little mitigation. Thus, although one type of disaster has natural causes and the other has economic causes, comparison provides insights for improving hazard assessment and mitigation policies. Instead of viewing such disasters as unpredictable and unavoidable "black swan" events, they are better viewed as "gray swans" that—although novel and outside recent experience—can be better foreseen and mitigated.

J. L. Stein
Professor of Economics, Emeritus, Division of Applied Mathematics, Brown University,
Box F, Providence, RI 02912, USA

S. Stein (✉)
Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL 60208, USA
e-mail: seth@earth.northwestern.edu

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1 Introduction

> The essence of the this-time-it's-different syndrome is simple. It is rooted in the firmly held belief that financial crises are things that happen to other people in other countries at other times; crises do not happen to us, here, and now. We are doing things better, we are smarter, we have learned from past mistakes.
>
> From: *This Time Is Different* by Reinhart and Rogoff (2009)

The first decades of the twenty-first century humbled two of the world's most advanced societies, who thought their technological and organizational prowess had tamed the danger of major disasters. One disaster—the March 11, 2011 Tohoku earthquake and tsunami—had natural causes and the other—the 2008 collapse of the US housing and financial markets—had economic causes. However, the two had a number of important similarities, which are illustrated by comparing the conclusions of commissions that investigated the disasters.

Japan's Fukushima Nuclear Accident Independent Investigation Commission (2012) wrote:

> the subsequent accident at the Fukushima Daiichi nuclear power plant cannot be regarded as a natural disaster. It was a profoundly manmade disaster—that could and should have been foreseen and prevented. And its effects could have been mitigated by a more effective human response… Our report catalogues a multitude of errors and willful negligence that left the Fukushima plant unprepared for the events of March 11. And it examines serious deficiencies in the response to the accident by TEPCO, regulators and the government… For all the extensive detail it provides, what this report cannot fully convey—especially to a global audience—is the mindset that supported the negligence behind this disaster. What must be admitted—very painfully—is that this was a disaster "Made in Japan." Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience, our reluctance to question authority, our devotion to 'sticking with the program', our groupism, and our insularity.

The US Financial Crisis Inquiry Commission's report (2011) identifies similar issues:

> Ben Bernanke, the chairman of the Federal Reserve Board since 2006, told the Commission a 'perfect storm' had occurred that regulators could not have anticipated; but when asked about whether the Fed's lack of aggressiveness in regulating the mortgage market during the housing boom was a failure, Bernanke responded, 'It was indeed. I think it was the most severe failure of the Fed in this particular episode'…"'Everybody in the whole world knew that the mortgage bubble was there', said Richard Breeden, the former chairman of the Securities and Exchange Commission…'I mean, it wasn't hidden… You cannot look at any of this and say that regulators did their job.'"

Both reports conclude that disaster resulted from failure to adequately anticipate and prepare for what occurred. In natural hazard terminology, disasters result from unrecognized or underappreciated weaknesses in hazard assessment and mitigation policies. This paper's goal is to explore this issue, drawing on results of our studies of the Tohoku (Stein and Okal 2011; Stein et al. 2012) and financial (Stein 2012) disasters. We first provide a brief overview of the two disasters, and then explore a number of important similarities between them. In particular, the policies that failed relied on models that proved inadequate for reasons including inaccurate conceptualization of the problem—due to both human and technical factors, use of a too-short historic record, and neglect of interconnections.

2 Disaster overview

Japan, in the boundary zone between three major plates, had long been afflicted by great earthquakes and the resulting tsunamis. Over a period of years, most recently in 2010, a government agency advised by some of Japan's leading seismologists had predicted what kinds of earthquakes could be expected in different parts of the country. This forecast was used to produce a seismic hazard map predicting the probability that the maximum ground acceleration (shaking) in any area would exceed a particular value during the next 30 years (Fig. 1), and to forecast the largest expected tsunami. To reduce the nation's vulnerability, high seawalls were built along a third of Japan's coastline, longer than the Great Wall of China (Onishi 2011a). Systems were set up to issue tsunami warnings so people in coastal areas could evacuate to higher ground. Structures were designed to survive earthquake shaking.

This planning proved inadequate on March 11, 2011, when a magnitude 9 earthquake struck the Tohoku coast, generating a huge tsunami that caused over 15,000 deaths and enormous damage. The hazard map, which showed the Tohoku area as having significantly lower hazard than other parts of Japan, significantly underpredicted the shaking and tsunami that occurred. The tsunami overtopped seawalls, and nuclear power plants proved to be much more vulnerable than anticipated. Although the warning system saved many lives (Ando et al. 2011), some people did not receive warnings and others ignored them. Thus, although mitigation efforts reduced the disaster significantly, the need for improvement was evident.

It has been argued that the earthquake and resulting tsunami should be viewed as rare, unforeseeably large, events (Chang 2011). These are termed "black swans" because prior to Europeans reaching Australia, all swans were thought to be white (Taleb 2007). However, as we will see, they are better viewed as "gray swans" that—although novel and beyond recent experience—could have been foreseen and mitigated.

Only three years before the Tohoku earthquake, the US economy suffered a financial disaster, despite policies that were believed to have made such disasters unlikely. Similar events had occurred since 1792, when a severe panic froze credit and nearly brought the young economy to its knees. Over the next 140 years, financial crises struck roughly every 20 years. Some grew into full-scale disasters, like the Great Depression of 1929 (FCIC 2011).

Policies and regulations adopted in 1933 and earlier were designed to prevent a similar disaster. The changes worked well. Although crises arose in sectors of the economy, such as the 1980s and 1990s agricultural crisis, savings and loan crisis, and the bursting of the "dot.com" bubble in technology stocks, these crises had no serious effects upon the financial system or the economy. After 50 years without a financial disaster—the longest such stretch in the nation's history—the Federal Reserve, Treasury Department, and White House saw financial disaster as a ghost of the past.

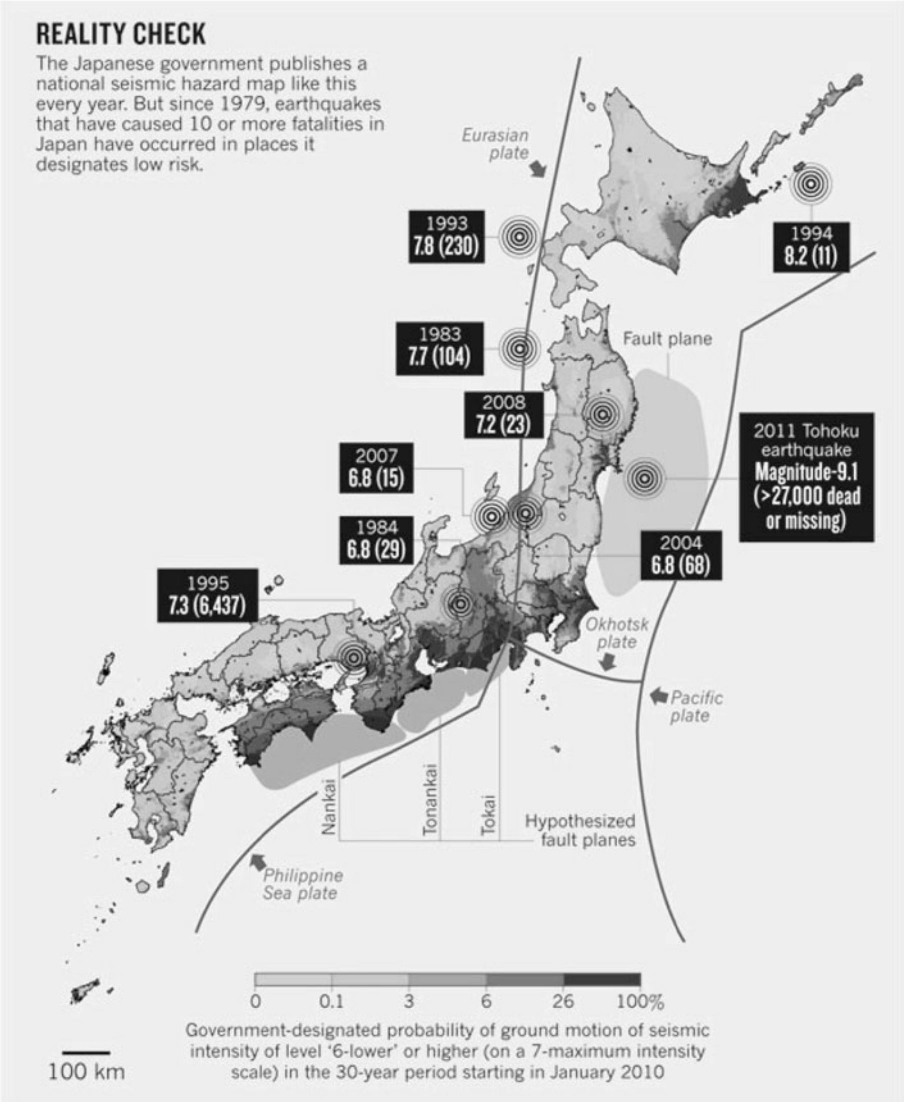

Fig. 1 Comparison of Japanese government hazard map to the locations of earthquakes since 1979 that caused 10 or more fatalities, all of which are shown as having relatively low hazard (Geller 2011)

This assumption proved disastrously wrong beginning in 2006 when housing prices that had been rising since 1975 collapsed (Fig. 2). The collapse was initially not viewed as having serious consequences, due to government officials' confidence in economic forecasting models (Appelbaum 2012). "We think the fundamentals of the expansion going forward still look good," Timothy Geithner, President of the Federal Reserve Bank of New York, told his colleagues in December 2006. This optimism proved incorrect. Increased foreclosures led to the collapse of securities based on housing prices.

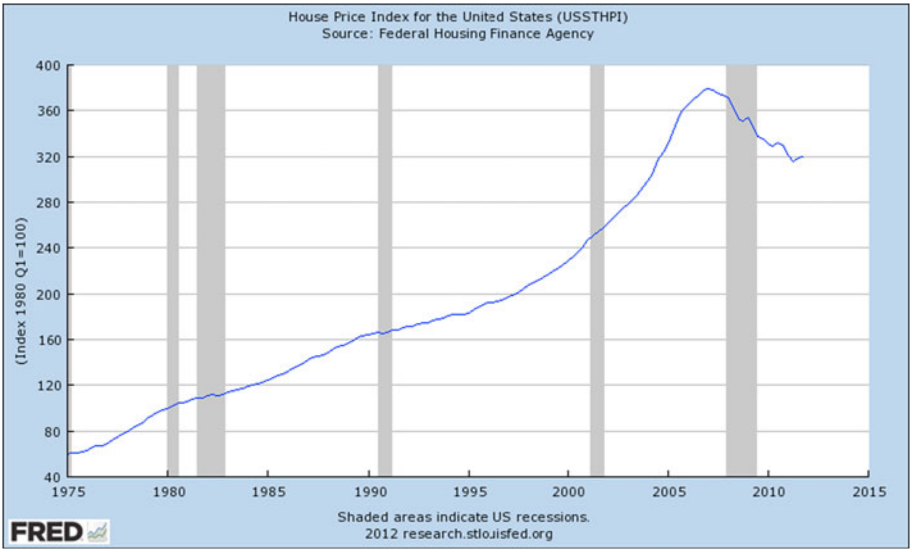

Fig. 2 The US house price index from 1975 to 2011. Prices are nominal, that is, not adjusted for inflation (Federal Reserve Bank of St. Louis)

Due to interconnections among banks and security houses, one sector's failure infected the other. By 2008, the financial system was in crisis, as shown in Fig. 3a by the financial stress index, a composite of financial indices including short- and long-term government and corporate interest rates (Federal Reserve Bank of St. Louis, National Economic Trends, January 2010). A number of major financial institutions were bankrupt or illiquid, inducing government intervention. Unemployment soared from less than 5 % in 2007 to 10 % in 2009, and remains above 8 % in 2012 (Fig. 3b).

Officials responsible for economic policy have argued that this financial crisis was unpredictable and unavoidable. The FCIC report and Stein (2012) discuss the failures of the Federal Reserve, Treasury, and International Monetary Fund concerning the crisis. As Alan Greenspan, former Chairman of the Federal Reserve Board, wrote in his retrospective in 2008 "Those of us who have looked to the self-interest of lending institutions to protect stockholders' equity, myself included, are in a state of disbelief." However, we will see that this "black swan" view is incorrect.

3 Similarities

The Tohoku and financial disasters resulted from unrecognized or underappreciated weaknesses in hazard assessment and mitigation policies. They have thus prompted extensive analysis of how such hazards could be better assessed and mitigated. Although the two disasters have been considered separately, this paper considers some analogous aspects.

The first similarity is the difficulty of identifying vulnerabilities. In the natural hazard literature, the term "hazard" describes the natural occurrence of earthquakes or other phenomena and "risk" describes the danger the hazard poses to life and property. Although the hazard is an unavoidable geological fact, the risk is affected by human actions, so the risk is the product of hazard and vulnerability (White 1974). A disaster occurs

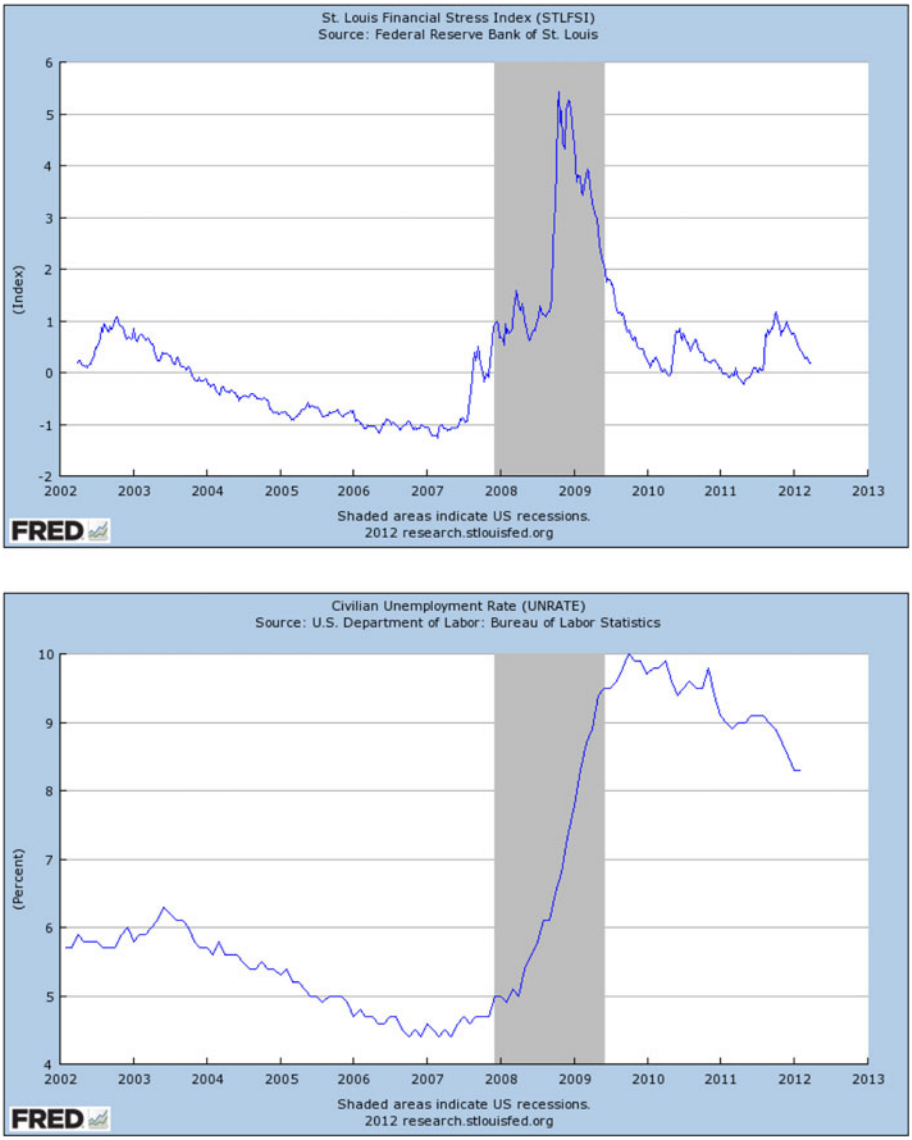

Fig. 3 Financial stress index (*top*) and unemployment rate (*bottom*) showing effects of the 2008 disaster (Federal Reserve Bank of St. Louis)

when—owing to high vulnerability—a natural event has major consequences for society. Vulnerability is increased as populations grow in dangerous areas and reduced by mitigation measures such as disaster-resistant construction. Similarly, we consider crises in specific sectors of the economy as hazards, and their consequences for disasters that can affect the entire economy as risks. The structure of the economy and government policies can increase or decrease the economy's vulnerability.

The second similarity is that mitigation planning relies on models of anticipated future effects to estimate the expected benefit of alternative mitigation strategies. However, these models are often inadequate. Mitigation policies used to prepare for both the Tohoku earthquake and the US financial crisis were based on widely accepted models that proved inadequate for reasons including inaccurate conceptualization of the problem, use of a too-short historic record, and neglect of interconnections. The resulting disasters illustrate the need to assess and significantly improve these models.

The third similarity is the challenge of balancing the costs and benefits of mitigation policies. Natural disaster mitigation policy relies on strategies including construction and land-use planning. Because these divert resources from other uses that could also do societal good, the issue is to assess the hazard and choose a level of mitigation that makes economic sense. Similarly, government financial regulations that minimize the economy's vulnerability can also inhibit desirable activity, so an appropriate balance is crucial. Thus, both natural and financial disaster mitigation involves optimizing the difference between the known cost and the estimated future benefits, and thus depends crucially on the assumed hazard model.

In discussing these similarities, we assume that readers are relatively more familiar with natural disasters and compare them with aspects of financial disasters that we believe are similar.

4 Hazards, risks, and vulnerability

Because a disaster often shows the society was more vulnerable than anticipated, it is useful to explore why these vulnerabilities were underappreciated or inadequately addressed by mitigation policies.

4.1 Vulnerability and interconnections

Vulnerability often results from interconnections, in which one failure causes others or several occur simultaneously. Thus, events that were thought to be very unlikely occur far more often than would have been expected by treating each portion of a system as independent, such that the probability of all occurring is the product of the probabilities of each occurring alone. This chain-reaction effect is common in technological accidents (Chiles 2002) but also occurs for natural disasters (Lomnitz and Castaños 2007). It can be described by Murphy's law that "anything that can go wrong, will, at the worst time." This is said to be named after Edward Murphy, one of a team in 1947 that used a rocket-powered sled to learn how much deceleration a pilot could survive. When the measuring instruments in a test read zero because they were installed backwards, Murphy made the observation bearing his name.

Planning for failure chains is hard, because it is often difficult to identify these vulnerabilities in advance, as shown by the sinking of the ocean liner *Andrea Doria* in 1956 (Moscow 1981). Such ships were considered unsinkable—invulnerable—for several reasons. First, they could not collide, because radar let them see in night and fog. Moreover, they were divided into watertight compartments and designed to float even if multiple compartments flooded. Still, Murphy's law prevailed. On a foggy night, as the *Doria* sped toward New York, the Swedish liner *Stockholm* rammed it. Apparently, one or both crews misread poorly designed radar displays. When the *Stockholm's* strong bow, designed to break through ice, hit the *Doria*, things went wrong. The bulkheads between compartments were designed assuming that if the *Doria* took on water, it could not tip, or list, more than 15°. However, these calculations assumed that once fuel tanks were emptied, they would be filled with seawater that provided weight to keep the ship level. In fact, because this required cleaning the tanks in port and disposing of the oily water, it was not done. After the collision, water poured into one side's tanks, while the other's stayed empty. Immediately, the ship listed 18°. Water from flooded compartments poured over the tops of the bulkheads and knocked out the generators needed to power the pumps, so flooding continued and the ship listed further. Lifeboat systems were also designed for less than 15° list, so boats on the high side could not be launched. Those on the low side were too far from the ship for people to get in, and so were lowered empty. Thus, only half of the boats could be used, and people had to jump down to them. Fortunately, the collision occurred on a calm summer night and other ships used their boats to rescue the passengers and crew.

Similar failure chains often arise in natural disasters, making vulnerability greater than anticipated. The fires after the 1906 San Francisco earthquake (Winchester 2005), which are thought to have done more damage than the actual shaking, are a prime example. Among the buildings that collapsed was a firehouse, in which the fire chief was killed. Fires broke out as natural gas lines burst and cooking stoves toppled. Firemen connected hoses to hydrants, but no water came out, because all but one of the water mains had broken. Attempts to dynamite firebreaks produced more fires. The fires burned for two days until stopped by a combination of rain, firefighting, and running out of things to burn. When all was over, much of the city was in ruins.

4.2 Tohoku and the US financial disaster

With the wisdom of hindsight, the Tohoku earthquake and the US financial disaster illustrate vulnerabilities that could have been recognized and reduced. For example, a significant component of the Tohoku disaster resulted from the destruction of the Fukushima nuclear power plant. The plant was vulnerable because the seawall protecting it was much lower than tsunami waves that could have been reasonably expected. Although this vulnerability arose because of limited knowledge when the plant was constructed in the 1960s, both the plant operator and government regulators—who were closely linked—ignored warnings of the higher hazard showed by new scientific results (Nöggerath et al. 2011; Onishi and Fackler 2011). Moreover, emergency generators were sited such that they were made inoperable by the tsunami. Measures with only moderate cost that could have reduced these vulnerabilities were not taken due to the pervasive "safety myth," illustrated by a protest song:

> If you walk across this country, you'll find 54 nuclear reactors
> School textbooks and commercials told us they were safe.
> It was always a lie, it's been exposed after all
> It was really a lie that nuclear power is safe.
> (Onishi 2011d).

Vulnerability is sometimes an unexpected consequence of mitigation. Residents of Japan's coast were proud of their tsunami defenses (Onishi 2011a, b, c). Although the seawalls cost billions of dollars and cut off ocean views, these were considered a small price to pay for eliminating the threat that had cost many lives over the past hundreds of years. People rode bicycles, walked, and jogged on top of the impressive walls. A school principal explained, "The seawall was an asset, something we believed in. We felt protected." However, this sense of safety discouraged some people from evacuating when the tsunami warning was issued (Ando et al. 2011; Onishi 2011a).

Analogous effects occurred in the US financial disaster growing out of the collapse of the housing market, as discussed by Stein (2012) and summarized here. From 1975 to 2007, housing prices grew steadily (Fig. 2) and the rate of growth increased dramatically from 1995 to 2007. This acceleration in the rate of growth, in excess of the rate of interest, was not sustainable. As in the Dutch tulip bubble of 1637 or the 1995–2001 US "dot-com" stock bubble, prices rose rapidly and then collapsed.

The house price bubble was fueled by low interest rates and subprime loans and mortgages issued to borrowers who had a high risk of default. Such borrowers were often called "NINJA"s for "no income, no job or assets." Borrowers were encouraged to lie about their finances via "no-doc" applications that would not be checked. The share of loans with full documentation decreased from 69 % in 2001 to 45 % in 2006.

The obvious hazard was that housing prices might collapse. The entire housing market was very vulnerable due to the risky loans, because although it was recognized that many borrowers were unlikely to be able to make loan payments from their income once initial low "teaser" rates ended, it was assumed that the loans would be refinanced from the appreciation of the houses' value. This could only work if housing prices continued to rise in excess of the interest rate. About half of such subprime mortgages taken out in 2006 were to extract cash by refinancing an existing mortgage into a larger mortgage loan. Government policies facilitated these risky loans. Neither Washington nor Wall Street recognized that continued borrowing to refinance without the income to pay the loan was an unsustainable "free lunch."

The vulnerability was produced by trillions of dollars of risky mortgages that were embedded throughout the financial system. Slices or "tranches" of mortgage-related securities, called derivatives because their values depended on the mortgages, were packaged, repackaged, and sold to investors around the world. Funds held packages of derivatives either directly or indirectly through investment in hedge funds. The purchases were financed by short-term bank loans. Neither the funds nor the banks worried about the rising debt, because their equity was rising as home prices rose.

These vulnerabilities were ignored, as discussed in the report of the Financial Crisis Inquiry Commission (FCIC 2011). Charles Prince, the former CEO of Citigroup, told the commission "As more and more subprime mortgages were created as raw material for the securitization process, more and more of it was of lower and lower quality. At the end of that process, the raw material going into it was actually of bad quality, it was toxic quality, and that is what ended up coming out the other end of the pipeline. Wall Street obviously participated in that flow of activity."

Because derivatives were not traded on organized exchanges, their prices were not transparent. This situation arose because of controversial government deregulation. In 1998, the Commodities Futures Trading Commission sought to regulate this trading, and General Accounting Office concluded that "the sudden failure or withdrawal of any one of these dealers could cause liquidity problems in the markets and could also pose risks to the others, including federally insured banks and the system as a whole." However, Federal Reserve Board Chairman Alan Greenspan, Secretary of the Treasury Robert Rubin, and others opposed regulation. Greenspan said "…regulation of derivatives transactions that are privately negotiated by professionals is unnecessary… By far the most significant event in finance during the past decade has been the extraordinary development and expansion of financial derivatives" (FCIC 2011).

Derivatives were not considered vulnerable due to an erroneous model. Securities firms like Lehman Brothers and Merrill Lynch bought packages of mortgages and sliced (tranched) them into successively riskier tranches. The income from the mortgages then flows like a waterfall. The senior tranche had the first claim, the mezzanine had the next, and the equity tranche got what if anything was left. The illusion was that this procedure diversified risk, so relatively riskless tranches could be constructed from mortgages of dubious quality.

When the house price bubble bursts, these interconnected vulnerabilities became apparent. Hundreds of billions of dollars in losses in mortgages and derivatives shook markets. Financial institutions had financed their purchase of these assets with debt from banks and money market funds. They were heavily leveraged in the sense that their assets and corresponding debt were large multiples of their net worth, the difference between assets and debt. Hence when asset values declined, the firms' net worth declined dramatically. Some firms (e.g., Lehman Brothers) went bankrupt and others (e.g., Bear Sterns) survived only via subsidized purchases or direct government bailouts.

Despite the view that the crisis could not have been foreseen or avoided, the FCIC argued otherwise. Washington and Wall Street ignored the flow of toxic mortgages and could have set prudent mortgage-lending standards. Government officials and regulators—many of whom had close ties to the financial sector—could have acted to protect the financial system, but chose not to.

5 Hazard models

Hazard mitigation planning relies on models of anticipated future effects to estimate the expected benefit of alternative mitigation strategies. However, these models often prove inadequate. The effects of both the Tohoku earthquake and the US financial crisis were much greater than anticipated based on widely accepted models. In hindsight, the models proved inaccurate for various reasons, some of which are similar in the two cases. These include use of a too-short historic record, inaccurate conceptualization of the problem, and neglect of interconnections. The resulting disasters illustrate the importance of carefully assessing models, recognizing the uncertainties involved, and improving them.

5.1 Tohoku: much bigger than expected

The Japanese seismic hazard map proved inaccurate because it assumed that the largest earthquakes of Tohoku would have magnitude below 8. The M 9 earthquake that occurred thus produced a tsunami much larger than had been expected (Fig. 4) that overtopped 10 m high seawalls. Such a giant earthquake was not anticipated due to several incorrect assumptions that reinforced each other, as summarized by Stein and Okal (2011) and Stein et al. (2012).

First, the short history considered was interpreted to show no record of such giant earthquakes or tsunamis. However, historical data before 1900 showed the presence of tsunamis much higher than 10 m. Second, it was assumed that magnitude 9 earthquakes would not occur because the subducting lithosphere was older than 80 million years. However, this model had been invalidated by the 2004 magnitude 9.3 Sumatra earthquake that generated the devastating Indian Ocean tsunami. Third, the presumed absence of giant earthquakes was interpreted as indicating that much of the subduction occurred aseismicallys, so most of the plate motion would not give rise to earthquakes. However, GPS data were inconsistent with this assumption. Fourth, the model ignored interconnections, by assuming that different segments of the trench would not break simultaneously, so the largest earthquake on any would have magnitude 8. However, four segments broke, giving

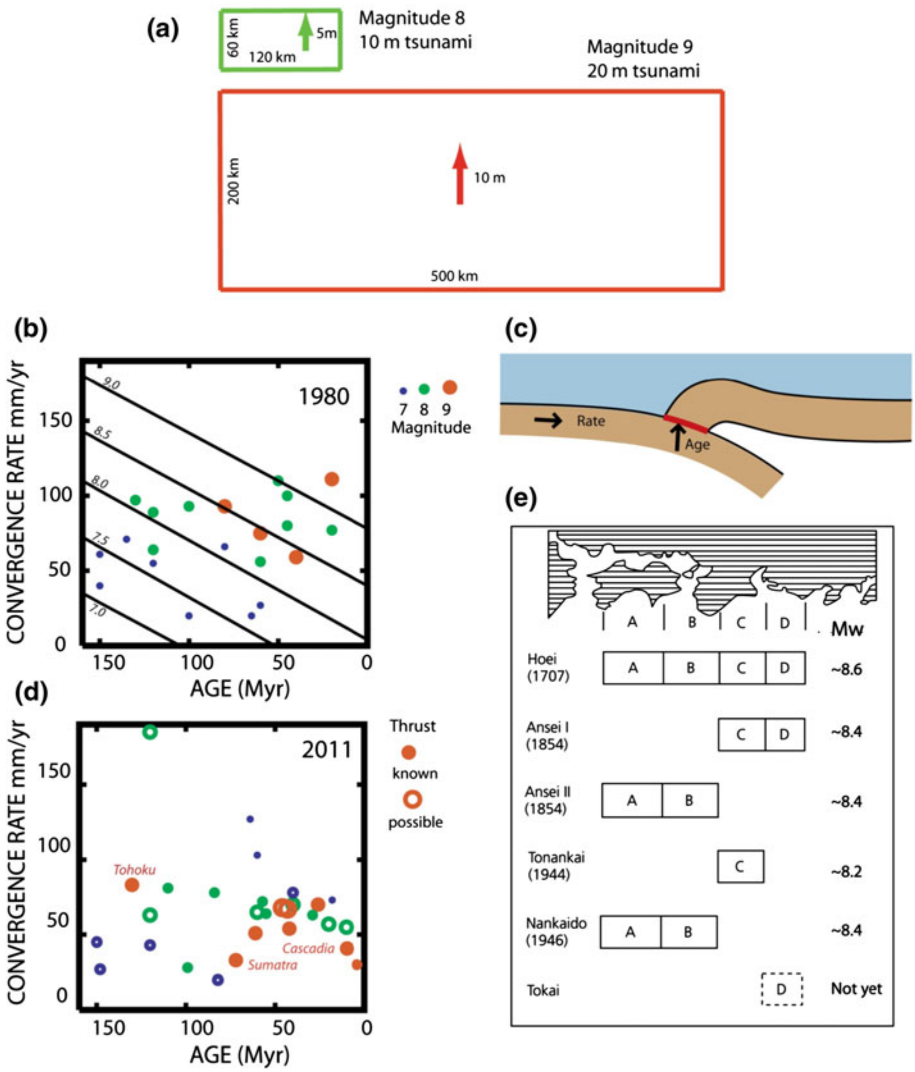

Fig. 4 What went wrong at Tohoku. **a** Illustration of the fault dimensions, average fault slip, and average tsunami run-up for magnitude 8 and 9 earthquakes. **b** Data available in *1980*, showing the largest earthquake known at various subduction zones. Magnitude 9 earthquakes occurred only where young lithosphere subducts rapidly. *Diagonal lines* show predicted maximum earthquake magnitude (Ruff and Kanamori 1980). **c** Interpretation of this result in terms of strong mechanical coupling and thus large earthquakes at the trench interface. **d** Data available today, updated from Stein and Okal (2007) by including 2011 Tohoku earthquake. **e** Earthquake history for the Nankai trough area (Ando 1975) illustrating how multiple segments rupturing cause larger earthquakes (Stein and Okal 2011)

a magnitude 9 earthquake. Although the new data and ideas would have changed the hazard map and mitigation measures eventually (Nöggerath et al. 2011; Stein et al. 2012), they were not fully yet appreciated and had not yet been incorporated in hazard assessment and mitigation policies. As summarized by Sagiya (2011), “If historical records had been more complete, and if discrepancies between data had been picked up, we might have been alert to the danger of a magnitude-9 earthquake hitting Tohoku, even though such an event was not foreseen by the Japanese government."

Following the earthquake, debate has arisen over whether the earthquake and resulting tsunami should be viewed as unforeseeably large events that should not be used to judge the map as unsuccessful, or whether they indicate systemic difficulties with the map. Geller (2011) favors the latter, noting that the map shows areas other than Tohoku as much more dangerous:

> The regions assessed as most dangerous are the zones of three hypothetical 'scenario earthquakes' (Tokai, Tonankai and Nankai). However, since 1979, earthquakes that caused 10 or more fatalities in Japan actually occurred in places assigned a relatively low probability. This discrepancy—the latest in a string of negative results for the characteristic earthquake model and its cousin, the seismic-gap model—strongly suggests that the hazard map and the methods used to produce it are flawed and should be discarded.

Similar discrepancies have occurred around the world (Stein et al. 2011, 2012; Kossobokov and Nekrasova 2012). For example, the 2008 Wenchuan earthquake (M 7.9) in China occurred on a fault system assessed to have low hazard based on the lack of recent seismicity. The 2010 M 7.1 Haiti earthquake similarly occurred on a fault mapped in 2001 as having low hazard, producing ground motion far greater than the map predicted. In some cases, the problem stemmed from considering a too-short historic record (Swafford and Stein 2007). In others, it stemmed from not using available data, such as GPS data that show motion across the Longmenshan Fault that failed in the Wenchuan earthquake (Meng et al. 2008).

Kerr (2011) described this situation as the "seismic crystal ball proving mostly cloudy around the world." This situation is striking, given that earthquake hazard mapping has become accepted and widely used to make major decisions with little discussion among users of the uncertainties involved. Although there has been some debate about how best to do it (Castanos and Lomnitz 2002; Bommer 2009; Panza et al. 2010; Wang 2011), there has been little assessment of the uncertainties in these maps or objective testing of how well they predict future earthquake effects.

The situation is starting to change, with considerable discussion among seismologists about how to improve hazard modeling. A number of researchers and programs (GEM 2012; CSEP 2011) plan to address it. Stein et al. (2011, 2012) suggest two approaches. First, the uncertainties in hazard map predictions should be assessed and clearly communicated to potential users. Knowing the uncertainties would enable users to decide how much credence to place in the maps, and thus make them more useful. Second, hazard maps should undergo objective testing to compare their predictions with those of null hypotheses, including ones based on uniform regional seismicity. Such testing, which is common and useful in similar fields, will hopefully produce measurable improvements.

The fact that hazard maps often do poorly is not surprising, because making them is a difficult enterprise involving assumptions about where and when large earthquakes will occur, how large they will be, and how much ground motion they will produce. Given the complexities of the earthquake process and our limited knowledge of it, many subjective choices are needed. As a result, maps depend heavily on their makers' preconceptions about how the earth works and have large uncertainties in the sense that plausible choices of key parameters predict quite different hazards (e.g., Newman et al. 2001; Hebden and Stein 2009). When the modelers' preconceptions prove correct, a map fares well. When they prove incorrect, a map does poorly. Predicting earthquake hazard has thus been described as playing "a game of chance of which we still don't know all the rules"

(Lomnitz 1989). Not surprising, nature often wins. The lesson of Tohoku is that that the limitations of hazard models should be borne in mind when using them to develop mitigation strategies.

5.2 The 2008 crash: genius fails again

The financial disaster of 2008 involved analogous problems. Since the 1970s, sophisticated mathematical models were used to develop arcane new financial instruments (Overbye 2009; Salmon 2009; Stein 2012). Few within the industry beyond their practitioners, termed "quants," understood how the models worked. Nonetheless, as described by Fischer Black, a leader in developing them, their theoretical bases were "accepted not because it is confirmed by conventional empirical tests, but because researchers persuade one another that the theory is correct and relevant" (Derman 2004). This acceptance was illustrated by the award in 1997 of the Nobel Prize in economics to Myron Scholes and Robert Merton for work based upon Black's, who died a few years earlier. Only a year later, Long Term Capital Management, a hedge fund whose directors included Scholes and Merton, collapsed and required a government-organized \$3.6 billion bailout. Unfortunately, this collapse—described in Robert Lowenstein's (2000) book *When Genius Failed*—did not lead to reassessment of the financial models, whose continued use in developing mortgage backed securities contributed significantly to the 2008 crisis.

Three failings of the financial models (Stein 2012) are analogous to those that caused the failure of the Tohoku earthquake hazard mapping. First, it was assumed that housing prices would continue to rise, based on the historic record from 1975 to 2006 (Fig. 2), so there was very little risk that house prices would fall. Real estate in the United States as a whole was considered a safe investment, though there would be regional and local differences. Moreover, the ominous rise in the ratio of house price index/disposable income to 2–3 standard deviations above the longer run mean was discounted. As in all bubbles, it was assumed that "this time is different" (Reinhart and Rogoff 2009)—this boom was sustainable. The government and finance profession refused to second guess the market, ignoring the unsustainability of the "free lunch."

Second, models erroneously assumed that bundling, slicing/"tranching" mortgages into derivatives made risky assets safe. The "apples in the basket" model assumed that one rotten apple implies nothing about the others. Thus, the probability that a few mortgages going bad would cause the entire tranche to fail was small. Based on this model, credit rating agencies gave high ratings to risky derivatives. However, the risk of default on mortgages is not independent, because if housing prices stopped rising fast enough, or the economy faltered, many borrowers would be unable to pay. Thus, a better model is "bread in the loaf"-one moldy slice implies that the next—or the rest of the loaf—is also. Packages of toxic assets, rather than riskless, were actually very risky.

Third, policy makers discounted the vulnerability posed by interconnections in the financial system and thus the possibility that the faltering housing market would impact the broader economy. The problem was not a lack of information, but excessive confidence in models that proved incorrect.

The incorrect models had enormous consequences because those using them gave little thought to their limitations. Derman (2004) argues that "the right way to engage with a model is, like a fiction reader or a really great pretender, to suspend disbelief and push it as far as possible… But then, when you've done modeling, you must remind yourself that… although God's world can be divined by principles, humanity prefers to remain mysterious.

Catastrophes strike when people allow theories to take on a life of their own and hubris evolves into idolatry."

6 Mitigation costs and benefits

Immediately following disasters, society's instinct is to ensure that a similar disaster will not recur by adopting mitigation policies to reduce vulnerabilities that the disaster illustrated. However, within a short time, the question of the costs and benefits of these mitigation measures arise, forcing society to confront the challenge of deciding how much mitigation is appropriate. More mitigation can reduce losses in possible future disasters, at increased cost. Less mitigation reduces costs, but can increase potential losses. One difficult aspect of balancing the costs and benefits is that the benefits have to be estimated using models—with the attendant uncertainties—to infer the probabilities of the future events. Another is that there are no unique or correct strategies, so society has to make tough choices. Hence although mitigation measures differ for natural and financial disasters, similar issues arise.

6.1 Rebuilding Tohoku

Natural disaster mitigation policy reduces vulnerability via strategies including construction and land-use planning. Because such policies have costs that divert resources from other uses that could do more societal good, the issue is to assess the hazard and choose a level of mitigation based on a complex set of political and economic criteria.

The situation following the Tohoku tsunami shows the challenge. Because the tsunami overtopped 5–10 m high seawalls, the extent to which the seawalls and other defenses should be rebuilt is a difficult and debated question. The issue is illustrated by the city of Kamaishi (Onishi 2011a). The city, although already declining after its steel industry closed, was chosen for protection by a $1.6 billion breakwater. A song produced by the government "Protecting Us for a Hundred Years" praised the structure "It protects the steel town of Kamaishi, it protects our livelihoods, it protects the people's future." However, the breakwater collapsed when struck by the tsunami. Nine hundred and thirty-five people in the city died, many of whom could have evacuated once warnings were given but did not, believing they were safe. Although the breakwater is being rebuilt, critics argue that it would be more efficient to relocate such communities inland, because their populations are small and decreasing. Otherwise "in 30 years there might be nothing here but fancy breakwaters and empty houses."

Because building coastal defenses adequate to withstand tsunamis as large as March's is too expensive, those planned are about 12 m high, only a few meters higher than the older ones (Normile 2012; Cyranoski 2012). These are planned to provide protection for the largest tsunamis expected every 200–300 years, augmented with land-use planning to provide some protection against much larger tsunamis. The defenses should reduce economic losses, while improved warning and evacuations should reduce loss of lives.

Although the policy issue is complicated and decided politically, its economic aspects can be conceptualized by considering how high a seawall to construct. A simple model, proposed by Stein and Stein (2012) and expanded here, based on economic modeling approaches (Stein 2012), illustrates a way to choose a strategy that optimally minimizes a risk-averse sum of the expected property losses from tsunamis and the cost of tsunami defenses.

At some point on the coast, we denote the cost of defense construction as $C(n)$, where n is the height of a seawall, which we use as our example, or a measure of mitigation in another method that increases resilience (Ewing and Synolakis 2010), such as the width of a no-construction zone. For a tsunami of height h, the predicted economic loss is a function $L(h-n)$, where $h-n$ is the height to which a tsunami will overtop a seawall, or otherwise exceed a design parameter. $L(h-n)$ is zero for a tsunami smaller than the design value n and increases for larger tsunamis. L includes both the damage itself and the resulting indirect economic losses. The probability of a tsunami overtop of height $h-n$ is $p(h-n)$, so the expected loss from a number of possible tsunamis over the life of the wall is

$$Q(n) = E\{L(n)\} = \Sigma_h p(h-n)L(h-n)$$

the sum of losses from tsunamis of different heights weighted by their probabilities. Thus, $p(h-n)$ describes the hazard, the occurrence of tsunamis of a certain size, and $Q(n)$ reflects the present value of the resulting risk, which also depends on the mitigation level n. The economically optimum level of mitigation minimizes the total cost, the sum of the expected loss and mitigation cost, where risk and uncertainty are taken into account. The term in brackets is the expected (mean) total cost, and $R(n)$ is a term added to reflect uncertainty in the predicted loss and aversion to risk

$$K(n^*) = \min_n\{[Q(n) + C(n)] + R(n)\}.$$

The cost of mitigation increases with the height of the seawall. Conversely, the expected loss in the future tsunamis decreases for taller walls. Thus, the total cost, the sum of the costs of mitigation and of the expected loss, has a minimum at n^*, the economically optimum level of mitigation (Fig. 5a). More mitigation gives less expected damage but higher total cost, whereas less mitigation decreases construction costs but increases the expected damage and thus total cost.

Because the expected loss and mitigation cost vary along the coast, the optimal mitigation level also varies. For sparsely populated areas, n^* shifts leftward, implying lower

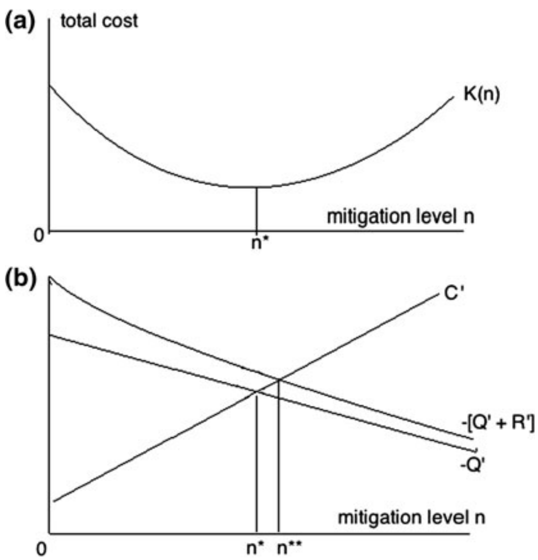

Fig. 5 **a** Variation in total cost, the sum of expected loss, and mitigation cost, as a function of mitigation level. The optimal level of mitigation, n^*, minimizes the total cost. **b** Same analysis shown by the derivatives. The optimal level of mitigation, n^*, occurs when the gain in mitigation $-Q'(n)$ equals the incremental construction costs $C'(n)$. Including the effect of uncertainty and risk aversion, the optimal wall height n^{**} occurs when the incremental cost equals the sum of the incremental mitigation and incremental decline in risk $R'(n)$

mitigation levels. Where expected losses are greater, such as urban areas or sites of critical facilities, n^* shifts rightward, justifying higher mitigation.

How this works can be seen by considering the derivatives of the functions (Fig. 5b). Because increasingly high levels of mitigation are progressively more costly, the marginal cost function $C'(n)$ increases with wall height. Similarly, $-Q'(n)$ is the marginal mitigation from a small increment of wall size. As the wall size rises, the gain in mitigation decreases. The lines intersect at the optimal point n^*, the highest level to which it pays to build the wall. If the intersection occurs where n^* is positive, it pays to build a wall. However, if even when the wall height is zero the incremental cost of a wall $C'(0)$ is greater than the incremental gain in mitigation $-Q'(0)$, it does not pay to build a wall.

The cost $K(n)$ reflects the mean value of the expected loss, but does not include the variance due to its uncertainty. For a given mitigation n, the total cost could be higher or lower than $K(n)$ because the tsunami loss can be higher or lower than its expected value, largely due to the uncertainty in the hazard model. In addition, we are risk averse in hazard mitigation planning. Risk aversion can be visualized using a game in which the probability of winning or losing \$1 is the same, but we place greater weight on avoiding losing than on winning. Risk aversion corresponds to the ratio of the gain to the loss necessary to induce the player to bet, which is greater than one.

The combined effects of uncertainty and risk aversion can be included by adding a risk term (Stein 2012) $R(n)$ to the mitigation term $Q(n)$. $R(n)$ is the product of the risk aversion and the variance of the estimated cost as a function of n. Greater risk aversion or greater uncertainty increase $R(n)$. Because the wall height should be increased as long as the marginal mitigation and decline in risk term $-[Q'(n) + R'(n)]$ exceeds the incremental cost of the wall, the optimum height increases from n^* to n^{**}.

Applying this approach requires various calculations. The first, the mitigation cost, is straightforward. The second requires tsunami models and the present value of predicted losses. The largest challenge involves calculating the probability of a tsunami of a certain height. The fact that the March tsunami was much greater than predicted showed that hazard models that predict the future occurrences of these events have large uncertainties, for many reasons including the fact that reliably estimating earthquake probabilities is very difficult even when long earthquake records are available (Savage 1991, 1992, 1994; Freedman and Stark 2003; Parsons 2008). In addition, tsunami defenses often prove less effective than planned (Yalciner et al. 2011).

Improvements should be forthcoming (Kanamori 2012) from more effective use of the earthquake history (McCaffrey 2007), paleotsunami record (Minoura et al. 2001; Nanayama et al. 2003), geodesy (Newman 2011; Simons et al. 2011), and other technologies. Even so, significant uncertainties will remain, but can be estimated and included through the $R(n)$ function. Thus, this formulation can be used to explore appropriate policies under alternative scenarios. It illustrates the importance of improving hazard models, because overestimating or underestimating the hazard leads to too much or too little mitigation.

Similar situations arise for other natural hazards including hurricanes and earthquake ground shaking. The goal is to assess the hazard and chose a level of safety that makes economic sense, because such mitigation diverts resources from other uses. Ideally, mitigation should not be too weak, permitting undue risks, or too strong, imposing unneeded costs. Ultimately, decisions on natural hazard mitigation policy are made through a political process also reflecting non-economic factors. Nonetheless, input from combined geophysical and economic analysis can improve the decision making.

6.2 Vulnerability and leverage: avoiding the next crash

Government regulations designed to minimize the financial system's vulnerability could have mitigated the 2008 US financial disaster. Crucial variables in the financial sector, its expected growth and vulnerability, depend on firms' leverage ratios L, defined as the ratio of their assets, A, to net worth, X. Net worth is the difference between assets and debts, D, so

$$X = A - D \quad L = A/X$$

Over time, the percent change in a firm's net worth is the difference between the return on its investments and the cost of interest on its debt

$$\begin{aligned} \mathrm{d}X/X &= \mathrm{d}(A - D)/X = \mathrm{d}A/X - \mathrm{d}D/X = (\mathrm{d}A/A)(A/X) - (\mathrm{d}D/D)(D/X) \\ &= RL - i(L - 1) \end{aligned}$$

where $R = (dA/A)$ is the return on investments due to the productivity of the assets and the capital gain due to the change in their value and $i = (dD/D)$ is the interest rate on the debt.

A drop in asset value, a negative R, can be viewed as a financial hazard due to market changes, and the resulting drop in net worth is the risk to the firm. Because the change in net worth depends on the change in asset value R times the leverage L, higher leverage makes the firm more vulnerable to a drop in asset value. Thus, risk = (hazard)(vulnerability) = (drop in asset value)(leverage).

In 2007, the major investment banks—Bear Stearns, Goldman Sachs, Lehman Brothers, Merrill Lynch, and Morgan Stanley—were operating with leverage ratios as high as 40. Thus, a 3 % drop in asset values would wipe out the firm. Such high leverage ratios made the economy vulnerable and helped convert the subprime crisis in the housing industry into widespread disaster.

Proposed new regulations could mitigate this hazard by reducing the vulnerability due to excessive leveraging. The question is what is a desirable degree of leverage? The debate centers on the Volcker rule, a proposed part of the Dodd-Frank financial reform act, which would limit the liabilities of the largest banks. However, without adequate leverage, financial markets do not provide a sufficiently high rate of return to attract capital. Critics thus argue that the rule will raise the cost of credit for companies wishing to invest in new plants, research and development, or increasing employment. Society has to balance the costs of mitigation against their benefits, and decide on the appropriate level of mitigation.

7 Summary

Comparison of a major natural disaster and a major economic disaster illustrates the presence of analogous aspects, such that studying the one provides insights for the other. Both disasters resulted from hazards that were inadequately assessed by existing models and vulnerabilities were unrecognized or underestimated. Preventing both types of disasters from recurring involves the difficult task of balancing the costs and benefits of mitigation policies, given that the benefits have to be estimated using models to infer the probabilities of the future events. Thus, although one type of disaster has natural causes and the other has economic causes, comparison between them provides useful insights for the challenging tasks of improving hazard assessment and mitigation policies.

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