Lessons from history: coastal cities and natural disaster

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Abstract

Purpose – This paper aims to connect the history of San Francisco's urban development, particularly the use of artificial fill along the coast, with the city's seismic history in order to explore whether San Franciscans have learned from recurrent natural disasters.

Design/methodology/approach – The paper uses historical analysis of primary sources, particularly scientific reports related to the 1906 and 1989 earthquakes. The theoretical approach draws on environmental history and natural disaster studies.

Findings – San Franciscans failed to learn lessons from earthquakes in 1868 and 1906. After the 1989 earthquake, experts reported that much of the damage had been predictable. Both policymakers and laypeople were surprised to discover the extent of scientific knowledge, given the poor preparation and outcomes.

Research limitations/implications – The brief treatment by no means represents a thorough review of the literature; the paper is intended to be provocative rather than comprehensive.

Practical implications – The paper suggests that coastal residents need to develop a new paradigm for viewing environmental change, including natural disasters, as an inherent element of dynamic coastal ecosystems. This mindset would help cities to better prepare for both future disasters and more gradual change to coastal landscapes, such as that likely to occur as a result of global climate change.

Originality/value – The study connects insights from the discipline of history to those of the earthquake sciences. It seeks to disseminate concepts from environmental history, such as the unnaturalness of natural disasters and the relationship of cities to nature, to an audience of policymakers and scientists.

Keywords Natural disasters, United States of America, Earthquakes, Coastal regions, Cities

Paper type Research paper

Introduction

This paper will explore how alterations to the coastal landscape of San Francisco contributed to its vulnerability to seismic activity, using the 1906 and 1989 earthquakes as case studies. From the city's founding, residents of San Francisco transformed its coast. By 1906, 354 acres of mud flats, shoreline swamps, and cove waters had been filled in and had become the sites of homes and businesses (Soulé, 1907). Regular seismic activity made these changes to the natural environment, which are common in coastal cities, particularly problematic in San Francisco, and these "made lands" suffered severe damage in the earthquakes of 1906 and 1989. The correlation between artificial fill and earthquake damage illustrates how these so-called natural disasters were not entirely natural. Instead, they stemmed from the interaction of natural seismic activity with human choices in building the city of San Francisco (Steinberg, 2000; Dyl, 2006).

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Planners and residents of coastal cities can learn additional lessons from this history, lessons that San Franciscans failed to learn by 1906 and even by 1989. My intention is to suggest connections between disciplines that seldom speak to each other on the topic of natural disasters and coastal environments. I make no claim that this brief treatment represents a thorough review of the literature; it is intended to be provocative rather than comprehensive. I suggest that coastal environments need to be understood as naturally dynamic, whether from seismic activity, hurricanes, or simply changing deltas and coastlines. The relationship between a city and the natural environment is a reciprocal one in which humans alter the environment – often with unforeseen consequences – but nature shapes the city as well. In order to learn from history, planners must move toward a paradigm that recognizes the dynamism of coastal environments, including understanding that disasters are endemic to certain areas and preparing accordingly.

Geography of San Francisco

Geographers and environmental historians distinguish between a city's site and its situation. Situation refers to a location's advantages in comparison to other cities. In San Francisco's case, its harbor provided great opportunities, but the city's site – the actual land it occupied – was less than ideal for urban development because of the ubiquitous sand dunes, hills, fog, and of course seismic activity. The *Annals of San Francisco*, the first history of the city, described the small city of 1855 as located in "about the most barren part of the district," surrounded by "low sand-hills, covered with coarse shrubs and scattered patches of grass." The geographer James E. Vance, Jr has called San Francisco's history one of "truly phenomenal investment" to render the land "somewhat less inimical to city-functioning than nature had made it" (Soulé *et al.*, 1998, p. 157; Vance, 1964). Over the course of the city's history, San Franciscans worked continuously to transform the site, or physical landscape, of their city.

The San Francisco peninsula consisted of a mix of rocky hills, sandy flats, alluvial valleys, and coastal marshes (see Figure 1). The eastern shore of the peninsula, where the first American settlements were located on Yerba Buena Cove, combined prominent rocky ridges with low lying valleys of alluvial soil. That soil was a mixture of sand and clay formed by the erosion of the hills and sand drifting in from the coast. Tidal creeks and marshes covered the floors of the valleys, and the Mission Bay lagoon and salt marsh made up much of the flat land that would become San Francisco (Lawson and Reid, 1908; Soulé, 1907; Humphrey, 1907). In 1852, a survey of coastal areas mapped the Mission Bay region as consisting of 300 acres of salt marsh and 260 acres of shallow lagoon that lay under water at high tide. Marshes penetrated north to what would become Mission Street between Seventh and Eighth Streets and Folsom Street between Fourth and Eighth. The swamps extended inland as far as the present-day Civic Center (Olmsted, 1986; Sharpsteen, 1942; Hansen and Condon, 1989). Bedrock lay far below the surface of sand or marsh; a boring sunk at the corner of Seventh and Mission Streets reached to a depth of 264 feet without hitting bedrock. When early city builders explored inland from the sand dunes and marshy valleys, they found forbidding hills – 43 on the 46 square miles of the peninsula (Lawson and Reid, 1908; Deering, 1936).

Although the early developers of San Francisco could clearly see the sand dunes and hilly topography that they faced, they had far less information about what lay beneath

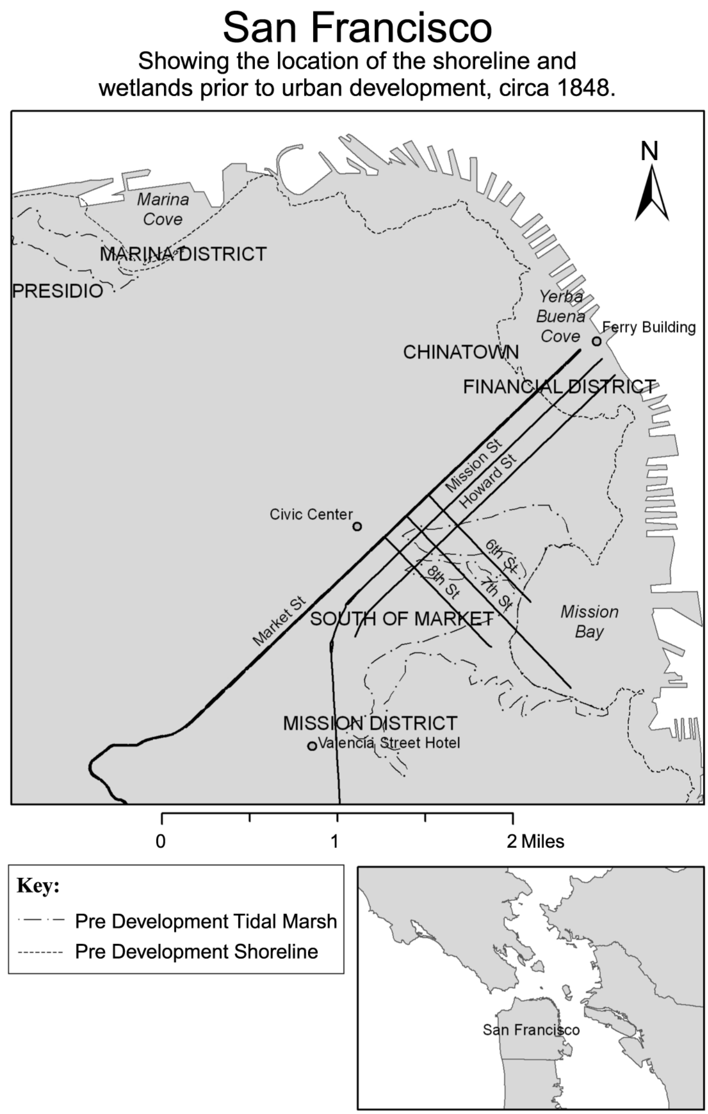

Figure 1.
San Francisco showing the location of the shoreline and wetlands prior to urban development, circa 1848

Source: City and County of San Francisco

the surface. In California, the very shape of the land is the product of frequent geological activity. Mike Davis has explained that the Mediterranean landscapes of California are anything but calm, stable ecosystems. Instead, "high-intensity, low-frequency events ('disasters') are the ordinary agents of landscape and ecological change" (Davis, 1998). The coastal regions of California sit on the boundary between two tectonic plates, the great sheets of the earth's crust that cover the planet. The mountain ranges of the state rose out of the collisions between these two plates, the Pacific and the North American, and their sliding against each other generates regular seismic activity. As a result, earthquakes large and small have always been part of daily life for San Franciscans. As many as 465 measurable earthquakes shook San Francisco between 1850 and 1906 (Branner, 1913; Bowden, 1967). Despite the frequency of small quakes, the city did not experience a major earthquake during its formative years. The last really destructive earthquake had taken place in 1836 before a substantial quake struck in 1868 (Young, 1912; Jordan, 1907). Thus, the city's early development occurred with little regard for local seismicity.

Urban growth and "making land"

The USA took control of San Francisco in 1846, and the town hired the surveyor Jasper O'Farrell to lay out lots and streets that would facilitate land speculation and growth. The new governor of California broke with Mexican precedent and granted the town title to beach and waterfront property that could be sold to raise municipal funds. O'Farrell laid out 444 beach and water lots, 80 percent of which were entirely covered with water at high tide. At the time of O'Farrell's survey, the population of San Francisco was only 459, but in July of 1848, more than 400 water lots sold for between 50 and 100 dollars each (Issel and Cherny, 1986; Phelan, 1905; Soulé *et al.*, 1998; Young, 1912). Even in San Francisco's infancy, speculators anticipated that the city's growth would depend on its port, and they did not hesitate to commodify both the land of the coast and the water of the bay, delineating and selling lots that consisted of mostly shallow water.

In 1848 and 1849, the new owners of water lots almost immediately began filling in their property. They built wharves and houses on piles, then leveled the inland sand hills and employed the sand as well as trash and debris to fill in the water around the new construction. At the time, this transformation of the original site represented nothing but improvement of the land to observers. The authors of the *Annals* matter-of-factly recounted how "great quantities of rock and sand were removed from places where they were only nuisances, to other quarters where they became of use in removing the natural irregularities of the ground, and making all smooth and level" (Soulé *et al.*, 1998, pp. 295-6). Urban improvement was under way in the form of "making land."

Commercial growth spurred by the gold rush drove the physical growth of San Francisco. The *Annals* described a "gradual march across the deep waters of the bay" as a "peculiar feature of the progress of the city." By the end of 1850, wharves reached out into the bay from eight different major streets. Within a few years, those original wharves had become public streets, lined first by stranded ships and wooden houses built on piles and then, within a few years, by new brick and granite buildings (Young, 1912; Soulé *et al.*, 1998, p. 293). The process of expansion out into the bay could not continue indefinitely, however, if nothing else because landowners feared that their property would lose value as it receded from the waterfront. In 1851, municipal government established a permanent waterfront for the city. The city's leaders had all been involved in speculation in water lots, so they protected their own interests with the legislation, and the land continued to increase in value. During a sale in the winter of 1853, small water lots measuring 25 feet by 59.9 feet sold for between 8,000 and 9,000 dollars each, with corner lots going for 15,000 to 16,000 dollars. These lots were under an average of eight-feet of water at low tide (Young, 1912; Olmsted, 1986; Soulé *et al.*, 1998).

Beginning in 1852, San Francisco's first steam shovel, known as the steam paddy, worked night and day shoveling sand from a 60 foot hill along Market Street between Second and Third streets. A steady stream of railway wagons and horse carts transported the sand between the areas of excavation and the shoreline, where it was deposited in Yerba Buena Cove as fill. The steam paddy could move as much of 2,500 tons of sand in a single day. It ran steadily between 1852 and 1854 and again from 1859 to 1873, when it used sand from the South of Market district to fill Mission Bay (Olmsted *et al.*, 1977; Olmsted, 1986; Soulé *et al.*, 1998).

San Francisco already incorporated 30 blocks of made land by the end of 1853, only four years after the gold rush had put the town on the map. In fact, gold rush wealth and pioneer spirit made such astonishing feats as leveling the hills of San Francisco and filling in the bay possible. After the initial boom had died down, the process of urban construction slowed as well. Charts from 1857 showed that little additional land had been added in the previous four years (Lawson and Reid, 1908; Olmsted *et al.*, 1973). Within those first few years, however, the human residents of San Francisco had made major changes to the city's site, leveling the ground and straightening the coastline to make it more amenable to a commercial city.

These transformations of the land and water naturally had consequences. Even in the short-term, evidence indicated that the new artificial fill was less than stable. On October 20, 1851, the weight of a packed crowd at the American Theater on Sansome Street between California and Sacramento caused the walls to sink two inches, inspiring doubts about the safety of the structure. In 1854, the city suffered from a recurrent problem with portions of buildings falling. Observers attributed the situation to a combination of inferior building materials and unstable ground, and the widespread settling of walls and buildings contributed to a slowing of construction on fill in the mid-1850s (Soulé *et al.* 1998; Young, 1912). Residents thus had an inkling that made land represented a hazard as early as the 1850s.

Put simply, the coastal area that became San Francisco originally consisted of shifting, unstable wetlands. Even without human action, the distribution of land and water could and did change. After a moderate earthquake in November of 1852, locals discovered that, on the western side of the peninsula, the waters of Lake Merced had burst through a wide sand bank, creating a channel to the Pacific. Previously, the lake had no apparent outlet, probably relying on an underground stream, and heavy rains that season may have weakened the sandy banks of the lake sufficiently to cause a collapse (Soulé *et al.*, 1998; Jordan, 1907). Such changes were a natural part of the coastal ecosystem, but they became increasingly problematic as a city grew up along the shores of the bay.

The city expanded inland and to the south even as it extended its commercial district out into the bay, and it encountered some of the same obstacles of site. In 1851, the Mission Plank Road (later to become Mission Street) connected the old Mission de Dolores and the scattered homesteads around Mission Bay with the developed area three miles away at Yerba Buena Cove. Builders initially planned to drive pilings to anchor the new road across the marshes, but in the vicinity of what is now Seventh Street, they failed to locate solid ground even with 80 foot pilings. Ultimately, they constructed the road on a wide platform of heavy planks that provided just enough stability for traffic, although the entire structure quickly sank several feet. With the explosive growth of the city, houses quickly lined the road in what became the South of Market and Mission districts (Olmsted, 1986; Young, 1912; Sharpsteen, 1942).

An earthquake on the Hayward Fault on October 21, 1868 highlighted the hazards of made land. The quake killed 30 people, and the total property loss was estimated to be as high as 5 million dollars. The bulk of the damage occurred on about two hundred acres of made land in the business district. Contemporary descriptions of the damage would have sounded familiar to survivors of 1906 or 1989. A house at Folsom and Fourteenth Street sank four feet into the ground. In several areas of the city, the ground settled as much as a foot and water welled up out of the earth. The *San Francisco Bulletin* observed that:

> [. . .] where the muddy deposits of the Bay have been crusted over by filling in sand, and these lands have been built upon, the foundation has always been insecure.

Statements like these show that San Franciscans were aware of the danger of earthquakes in their city and of the particular risks posed by made land, at least at those moments when nature reminded them (Young, 1912; Lawson and Reid, 1908; Geschwind, 2001; Huber, 1930, p. 269).

The geologist Bruce A. Bolt has written that political action to reduce risk in the aftermath of an earthquake has a half-life of only a year or so, and that was certainly the case in San Francisco in 1868. In the first days after the shock, the *Alta California* warned of the presence in the city of too many buildings that were "dangerous under any circumstances to human life" because of thin walls, slight foundations, and inadequate supports. However, the city desired to wipe the earthquake from memory before it could have a negative economic impact, and the Chamber of Commerce appears to have suppressed a report prepared by a committee studying the quake. No copies of the report have ever been located, although references to the investigation can be found in the *Alta California* and the *San Francisco News Letter* during 1868 and 1869. The tension between risk reduction and a return to normal development, driven by economic motives of minimizing cost and promoting growth, led San Franciscans to suppress the lessons they could have learned in 1868 (Bolt, 1999; Huber, 1930; Prescott, 1982; Steinberg, 2000).

Instead, the made lands along the coast and the soft soil of the adjacent valleys became the site of nearly all the commercial buildings of San Francisco, including the wholesale district, many of the city's hotels, the financial district, and the Mint and Post Office, as well as the site of working-class residential districts. By 1906, the coastal land that had once been sand dunes, wetlands, and even waterways housed one-sixth of San Francisco's population and most of its commercial ventures. Not coincidentally, these areas of the city also experienced the most severe damage when a major earthquake struck the city that year (Soulé, 1907; Lawson and Reid, 1908).

The 1906 earthquake and fire

On the morning of Wednesday, April 18, 1906, a massive earthquake shook San Francisco and the surrounding region. The two sides of the San Andreas Fault shifted as the Pacific plate crept north and the North American plate rumbled southward. The plates moved as much as 21 feet in parts of Marin County, just a few miles north of San Francisco across the bay, and as much as eight feet on the peninsula where the city of San Francisco nestled at the northern end. The Fault, which had been mapped ten years earlier by the University of California geologist Andrew C. Lawson, passed just three miles to the west of San Francisco, and the epicenter of the earthquake was located about a mile off the coast of Daly City, a suburb just south of the city. The quake has been estimated at 7.9 on the Richter scale, and the destruction extended for at least 350 miles along the north-south line of the Fault and for 35 miles on either side, covering a total area of 25,000 square miles. Within San Francisco, the earthquake was followed by a devastating fire that swept through the city for three days. The earthquake had shattered the pipes of the city's water system, including both the distribution system within the city limits and the main conduits into the city, and the fire department struggled to get the flames under control with little access to water. The fire ultimately destroyed half the acreage of the city – 514 city blocks – and over 28,000 buildings.

As the city recovered and rebuilt after the disaster, understanding the earthquake became a top priority for the scientific community. Even before the last of the fires were extinguished, the governor of California appointed what became the State Earthquake Investigation Commission under Lawson's leadership. The Commission would produce an impressive report detailing the scope of the damage and outlining several theories about the quake (Lawson and Reid, 1908; Fradkin, 2005). The detailed reports of the Commission and other scientists allow us to relate the damage at particular sites within San Francisco to the history of changes made to the land over a half-century of urban development. The decisions made more than 50 years earlier to buy and sell water lots and extend the city out into the bay proved costly in 1906.

The scientists discovered a correlation between the degree of earthquake damage and the distance from the Fault. A more important factor, however, was the type of ground, with made land being the worst. For example, Telegraph Hill and the Ferry Building stood only a quarter of a mile apart on the eastern shore of San Francisco, essentially equidistant from the Fault and the epicenter. However, damage on the made ground at the Ferry Building was similar to that along the Fault itself, whereas on the rocky summit of Telegraph Hill even a number of brick chimneys remained intact. The Commission's report concluded that:

> [. . .] the degree of intensity which prevailed at any locality in the city depended chiefly on whether the underlying formations are firm rock or incoherent material more or less saturated with water" (Lawson and Reid, 1908, p. 341).

This conclusion has been corroborated by modern earthquake science.

The most dramatic human crises of the earthquake occurred on areas of made land. In the Mission District, the four-story Valencia Street Hotel sank three storeys, resulting in the deaths of an estimated 200 people. The site of the hotel had been a lake in 1776 when the Spanish arrived in the region and a swamp until the 1870s. Less than one-third of the wood frame dwellings in this section of the Mission remained standing after the earthquake (Barker, 1998; Hansen and Condon, 1989; Lawson and Reid, 1908). In the area of Sixth and Howard, where cheap rooming houses collapsed against each other in a chain reaction that killed hundreds of residents, the ground had shifted 7 feet. As the historian Gladys Hansen wrote, this land had been "a portion of Mission Swamp once known as Pioche's Lake," which had been created by the 1868 earthquake only to be filled in the intervening decades (Board of Public Works, 1911; Hansen and Condon, 1989). Each of these localized disasters – and much of the South of Market district as well as parts of the Mission – fell within two areas of particularly high seismic intensity identified by the State Earthquake Investigation Commission. One such area extended from Eighth and Mission to Fourth and Brannan and traced along the original shore of Mission Bay, encompassing land that had once been a tidal marsh or a portion of the bay itself. The Commission described another as a "'made' land tract along the former course of Mission Creek," which extended unevenly from Ninth and Brannan to Nineteenth and Dolores, passing near the site of the Valencia Street Hotel (Lawson and Reid, 1908, p. 236).

Of course, the type of ground was not the only factor in the degree of destruction caused by the earthquake. The quality of construction played an important role as well. Part of the old course of Mission Creek was the site of the Southern Pacific railway tracks, which survived the earthquake because of a strong foundation. The railroad lands had also been filled in with broken rock from nearby hills rather than the less solid mixtures of sand, trash, and whatever material was available used in many older filled areas (Lawson and Reid, 1908). Another survivor was the United States Post Office building at Seventh and Mission. Just to the southwest of the post office, the streets were "deformed into great waves, some with an amplitude of at least three feet." Some sections of the street sank 4 feet, and the pressure crushed manholes with concrete walls a foot thick. The post office building had been constructed on 20 foot piles, however, and it suffered damage but survived the earthquake (Lawson and Reid, 1908, p. 238; Hansen and Condon, 1989; Sewall, 1907). The greatest danger resulted from the confluence of unstable ground and poorly constructed buildings, such as the multi-story wood frame buildings that served as cheap rooming houses.

The effects of the earthquake along the waterfront provide another example of the intersection of made land, modern construction, and seismic damage. The problem of instability, manifested in the form of gradual subsidence, was well known to local experts such as city engineer C.E. Grunsky before 1906. Five years earlier, Grunsky's Board of Public Works had begun a project of recording subsidence in the area. In a single year, part of Harrison Street subsided 0.17 feet (2.04 inches) between Fifth and Sixth Streets while Sixth Street sank 0.10 feet (1.2 inches) between Howard and Channel. The next year, the city engineer recorded a maximum subsidence of 0.22 feet (2.64 inches) on Harrison and 0.17 feet (2.04 inches) on Sixth (Board of Public Works, 1902, 1903). Because of this "constant tendency of the whole district to subside from year to year," in the words of the State Earthquake Investigation Commission, cable car tracks on lower Market Street had been constructed on piles to maintain their grade. When the earthquake hit, the tracks remained largely intact while the street on both sides sank. The Commission concluded that the earthquake had caused the fill "to settle together and occupy less space," sinking anywhere from a few inches to as much as three feet. In general, the damage was greatest closest to the waterfront (Lawson and Reid, 1908, pp. 233-7). The most noticeable survivor in this section of San Francisco was the Union Ferry Building, which suffered damage but possessed a sufficiently strong foundation that it remained standing even though its site was 700 feet east of the original shoreline of the bay (Soulé, 1907; Douty, 1977).

Of course, buildings were not the only structures affected by the shaking. Water pipes, gas pipes, electric light conduits, and city sewers were all badly damaged, especially where they crossed filled ground. Many of the sewers were still constructed of brick, but water and gas pipes made of cast iron also broke apart. The 44 inch wrought iron pipe of the Crystal Springs conduit, which transported San Francisco's water supply up the peninsula to the city's reservoir system, suffered ruptures in seven places where it crossed the swamps south of San Francisco. Another conduit, the Pilarcitos, ran through what engineers had undoubtedly considered to be a convenient narrow valley but which in fact marked the San Andreas Fault. When the Fault moved, the earthquake shattered the 30 inch iron pipe, throwing it 60 feet to the side. At least 19 different ruptures occurred along a 6 mile stretch; in places, the pipe had been either pulled apart or telescoped by as much as 6 feet (Schussler, 1906; Humphrey, 1907; Derleth, 1907).

In summary, the State Earthquake Investigation Commission found that the effects of the earthquake varied drastically in San Francisco and the surrounding region depending largely on the type of ground. In most of the northeastern section of San Francisco, where buildings were constructed on the bedrock of the hills, the damage was limited to chimneys falling and "slight cracking of brick work." The East Bay cities of Oakland and Berkeley similarly suffered relatively slight damage because of their rocky base. On the other end of the spectrum was made land, which the scientists found to be less stable even than natural alluvium. They declared that made land represented unequivocally dangerous building sites (Lawson and Reid, 1908). San Francisco was far from unique among cities in transforming its landscape as it grew. The circumstances of the gold rush and the challenges of San Francisco's particular site, with its shortage of flat land for building, abundance of sand hills, and reliance on its harbor, made for a particularly dramatic transformation of the land. Perhaps more importantly, the seismic activity in the region made San Franciscans' choice to develop their city by "making" land and otherwise altering its site a problematic one.

The 1989 Loma Prieta earthquake

An examination of the next major earthquake to strike the region – the Loma Prieta earthquake, which occurred on another stretch of the San Andreas Fault on October 17, 1989 – helps reveal whether San Francisco learned from its experience in 1906. In fact, this quake's magnitude of 7.1 made it more of a "mid-major" earthquake, and the epicenter was 60 miles south of San Francisco in the Santa Cruz Mountains. The Loma Prieta earthquake killed 63 people and caused an estimated 10 billion dollars of damage throughout the region. However, despite the distance of the epicenter from San Francisco and the knowledge of hazards that could have been gleaned from past experience, the damage from the 1989 earthquake had disturbing parallels to that of 1906. The patterns of destruction again reflected the hazards of a coastal city in a seismically active area, and they showed that the city had absorbed few lessons from its previous disasters. The neighborhoods that suffered the worst damage in 1989 included the South of Market district and the Mission, and specific locations of severe destruction even paralleled those of 1906 (Pease and O'Rourke, 1998; Clough *et al.*, 1994).

The neighborhood that dominated the news, however, was the Marina District, located on the northern end of the San Francisco peninsula on the bay. The Marina District had not been heavily developed in 1906, when it was known as Harbor View – in fact, one might say that much of it did not exist. Like other coastal sections of San Francisco, the area that became the Marina consisted of sand dunes, tidal marshes, and sloughs in the mid-1850s. Development of the area began in the 1860s and included some use of artificial fill to create land, but it remained sporadic. In 1906, the district was a mixed-use area combining several industrial employers and working class homes. Marina Cove remained and was 12 feet deep at high tide, although it had been enclosed by a rim of artificial fill that included segments of a seawall built in the 1890s. The development of the district, and particularly the use of artificial fill to maximize the land area, was thus incomplete when the 1906 earthquake struck, although the neighborhood did report severe ground shaking and settlement in that year (Bonilla, 1992; Bolton, 1998; O'Rourke *et al.*, 1992).

Redevelopment of the district began in 1912 when it was selected as the site for the 1915 Panama Pacific International Exposition. Hydraulic filling of Marina Cove took place from April to September of 1912 as one million cubic meters of sand and mud were pumped into the cove. The temporary buildings of the Exposition were constructed on piles as much as 75 feet long, although even those did not come close to reaching bedrock, which was as far as 265 feet below the surface (Bonilla, 1992; Bardet *et al.*, 1992; Harris and Egan, 1992). After the Exposition, the area became a residential district. By 1989, 14,000 people lived in the neighborhood, many of them in one- to four-story wood frame apartment buildings that dated from the late 1920s (Bonilla, 1992; Scawthorn *et al.* 1992).

When the 1989 earthquake struck, the made land of the Marina District became a ground-failure zone. The neighborhood suffered from widespread liquefaction, sand boils, settlement, buckling, and cracking. Seven buildings collapsed, and at least 63 others became unsafe to occupy (Harris and Egan, 1992; Bardet *et al.*, 1992; Scawthorn *et al.*, 1992). In an echo of 1906, gas pipes, sewer pipes, and water pipes shattered in the unstable ground. Fires broke out within minutes, and firefighters found little water available from either the municipal water supply system (MWSS) or the separate auxiliary water supply system (AWSS), which had been constructed after the 1906 crisis to prevent another such disaster. The MWSS had been disabled by 123 main and service-line breaks in the Marina district caused by the liquefaction and settlement of the ground. The AWSS remained intact in the district, but it lost most of its water pressure because of breaks across town in the South of Market. A major fire in the Marina was finally controlled after more than four hours and 7.4 million dollars of damage with the assistance of San Francisco's lone fireboat and the city's Portable Water Supply System, developed just a few years before to provide a means of constructing mobile, above-ground water mains. The city had narrowly escaped a conflagration eerily reminiscent of 1906, and at least one firefighter suggested that the city had gotten lucky; he believed that the unusual lack of wind on the night of October 17 had been at least as responsible for saving the neighborhood as the city's firefighting technologies (O'Rourke *et al.*, 1992; Scawthorn *et al.*, 1992).

One of the most striking elements of the studies that followed the 1989 earthquake was the degree to which scientists reported few surprises in the areas that had suffered damage, the classes of buildings most at risk, and the type of ground on which damage, particularly liquefaction, had occurred. Experts had essentially predicted the disaster, although not of course its timing, and the pattern of damage largely reflected lessons that could have been learned from 1906 or even 1868, notably the hazard presented by artificial fill. However, although scientists and other earthquake experts were unsurprised by most of the effects of the 1989 earthquake, government and business leaders were surprised. And just as strikingly, they were shocked to learn that earthquake experts had known much of what would occur, yet preparations had nonetheless been insufficient – and disaster plans had largely failed to incorporate this expert knowledge (National Research Council, 1994; Clough *et al.*, 1994; Scawthorn *et al.*, 1992).

Despite the advancements in scientific knowledge over the twentieth century, San Francisco's experience with the Loma Prieta earthquake in many ways repeated the mistakes of 1868 and 1906. Once again, city leaders and residents seemed to have failed to learn lessons from previous seismic events that could have mitigated the next disaster. For example, despite the dangers of made land so graphically demonstrated in 1906 and clearly identified by scientists, the city created another large area of artificial fill just six years later in the Marina District. In 1989, although earthquake experts were unsurprised by the localized disasters, their knowledge had again failed to trickle down to either political leaders or regular citizens.

Conclusion: lessons from history

San Francisco's susceptibility to earthquake damage thus began with a location subject to regular seismic activity and intensified as the process of urban development created made land. Altering the land to create prime real estate in San Francisco also created unstable ground that was subject to severe shaking each time an earthquake struck the city. In 1906, the concentration of 400,000 people in an urban center combined with the ways in which San Franciscans had reshaped the site of their city to transform a seismic event into a disaster. This history shows how so-called natural disasters, like cities themselves, take shape because of a complex interaction of natural forces and human activities (Steinberg, 2000). Events like earthquakes – and, for other cities, floods, hurricanes, tornadoes, and wild fires – represent recurrent threats to urban areas. They are part of urban ecosystems even though most observers perceive them as anomalous "natural disasters" and react by rebuilding and restoring the city, often with minimal regard for reducing the future vulnerability of the urban environment.

The natural environment is dynamic, particularly in a place like California where seismic activity is common and climate and rainfall vary widely from year to year. However, many people, including city builders, possess implicit assumptions of stability in urban environments. City leaders and developers assume that the natural landscape will remain stable even as the built environment undergoes periodic reconstruction. In this paradigm, the only evolution that takes place results from human activity; the city is apart from nature, or nature itself is expected to be immutable. However, in seismically active areas like San Francisco – or in coastal areas of California, Florida, and the Gulf Coast – the landscape is naturally fluid and shifting. Under normal circumstances, human residents can manage these changes, for example by re-routing or filling in river courses, building seawalls and waterfront piers, and restoring beaches. Humans and their cities are less prepared for sudden, catastrophic events that transform the landscape, such as earthquakes and hurricanes.

Instead of change occurring only through human initiative, environmental history demonstrates that the relationship between the natural environment and the city is a reciprocal one in which humans alter the environment – often with unforeseen consequences – but nature in its various manifestations shapes the city as well. This history reveals how we, as urban residents and planners, need to develop new paradigms for understanding the relationship between our cities and the dynamic land beneath them. This is particularly true for coastal cities where both disasters and the more gradual processes of coastal erosion and global warming make for dynamic environments. Coastal residents, planners, and policymakers need to move away from the assumption that the land is stable and unchanging, simply something that is acted upon by humans rather than being an agent of history in its own right, and we need to understand that change – even sudden change in the form of disaster – is a natural and inevitable element of coastal ecosystems. This is the broad lesson that we can learn from San Francisco's seismic history.

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