



EERI Earthquake Reconnaissance Report: M7.1 Anchorage Earthquake on November 30, 2018



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PREFACE

The M7.1 November 2018 Anchorage earthquake was the largest magnitude event in North America in the vicinity of a large population in the last 55 years. The absence of fatalities and serious injuries was initially viewed by many as a sign of earthquake readiness; however, after a year-long investigation of the earthquake impacts, it can be confidently stated that readiness partially helped but that it was the blessing of the large earthquake depth and relatively smaller shaking intensity compared to the design-based earthquake that prevented a more serious catastrophe.

During the course of the Earthquake Engineering Research Institute (EERI) field earthquake-reconnaissance effort and data analysis I co-led over 2019, many lessons were learned. In many aspects, it was fortunate that Southcentral Alaska building stock diversity manifested in the region as a large test bed to observe how building practices impacted their earthquake damage levels. Furthermore, the well-instrumented Anchorage Bowl, including instrumented structures, and the good documentation of earthquake impacts by many stakeholders, including the EERI Reconnaissance Team, will constitute a learning opportunity from this event to inform research, codes, and practice for years to come.

The report covers seismology and tectonics, geotechnical impacts on buildings and infrastructures, building codes and their impact on the earthquake damage, structural impacts on buildings, nonstructural damage, performance of instrumented buildings, impacts on schools and hospitals, performance of bridges, and damage to lifelines and utilities.

I am pleased to introduce this comprehensive EERI Learning from Earthquakes report on the first anniversary of the earthquake, in which we are sharing observations and lessons learned with the public, earthquake engineering community, policymakers, emergency agencies, and all other stakeholders. One year after the earthquake, which by no means can be viewed as the Big One, Alaskans are still recovering. Many residences, businesses, schools, and lifelines are still in the process of repairing earthquake damage, whereas many others are financially struggling while awaiting federal and state assistance. In this report, we highlight observations that can help the region determine its level of readiness for the Big One. I am hoping this report provides a humble contribution to reduce future earthquake losses and help build safer structures in seismic regions worldwide.

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November 30, 2019

1 INTRODUCTION

1.1 Overview of the November 30, 2018, Anchorage Earthquake

On November 30, 2018, at 8:29 a.m., Alaska Standard Time (AKST), Southcentral Alaska, the most populous region in Alaska, was violently shaken by an M_w 7.1 earthquake that was 46 km (29 miles) deep and epicentered at 61.346°N, 149.955°W, 12 km north of Anchorage and 19 km west of Eagle River. Shortly after, at 8:35 a.m., AKST, an M_w 5.8 aftershock and a widely broadcasted tsunami warning further terrified Alaskans and the nation, especially after early unconfirmed reports of widespread damage in the region. The event affected some 400,000 residents in the Anchorage Metropolitan Area in the Anchorage and Matanuska-Susitna (Mat-Su) Boroughs. The earthquake caused widespread damage to roads and highways, nonstructural components, non-engineered buildings (which do exist widely in the region), older buildings, and buildings and infrastructure on poorly compacted (and uncompacted) fills. Minor structural damage in newly engineered buildings was observed. The main shock generated a vigorous aftershock sequence with over 10,000 aftershocks in the first 9 months. Over 300 aftershocks were felt; 50 of which were larger than M_w 4+ and seven of which were M_w 5+.

Building stock diversity manifested the region as a large test bed to observe how building practices impacted their earthquake damage levels. The Anchorage Bowl is heavily free-field instrumented, and more than eight structures in Anchorage are well instrumented with structural arrays. The prevailing peak ground acceleration (PGA) in the region was $0.20g$ – $0.32g$, although individual sites may have experienced stronger shaking due to local soil conditions. In general, the PGA at most sites was about 50%–60% of the design-based earthquake (DBE) acceleration.

After a year-long investigation following the earthquake, it can be confidently stated that Southcentral Alaska's built environment has not yet been seismically tested on Nov 30, 2018, even with a DBE, let alone stronger shaking.

1.2 EERI Reconnaissance Team Members

The Earthquake Engineering Research Institute (EERI) Field Reconnaissance Team comprised four members balanced between academics and professionals as following:

1. Wael M. Hassan, Associate Professor of Structural and Earthquake Engineering, University of Alaska, Anchorage, AK (team co-leader and leader of structural engineering reconnaissance)
2. John Thornley, Associate Principal, Golder Associates, Anchorage, AK (team co-leader and leader of geotechnical engineering reconnaissance)
3. Janise Rodgers, Chief Operating Officer and Project Manager, GeoHazards International, Menlo Park, CA
4. Christopher Motter, Assistant Professor of Structural Engineering, Washington State University, Pullman, WA

Several other individuals facilitated and assisted the team in its mission, as outlined in the *Acknowledgments*.

1.3 EERI Reconnaissance Team Activities

The EERI Reconnaissance Team officially started its mission the day following the earthquake, although team co-leaders were already working on the ground conducting independent personal reconnaissance immediately following the earthquake on November 30, 2018. The field mission comprised surveying, curb inspection, and thorough damage inspection of hundreds of structures over the course of 10 months following the event. The majority of field inspections took place in December 2018 and January 2019. However, significant field reconnaissance was performed by the team co-leaders in the spring and summer of 2019 following snow melting, which relatively exacerbated damage in the built environment and revealed original damage that was hidden by snow. Few field inspection activities were continued through September 2019 by the team co-leaders.

The EERI Reconnaissance Team co-leader Wael Hassan was in charge of leading the structural and nonstructural damage investigation, while the team co-leader John Thornley was in charge of leading the geotechnical and seismological investigation. The first phase of field reconnaissance (December 2018 to January 2019) by the team included 4 weeks of field reconnaissance by team co-leader Wael Hassan, 2 weeks of fieldwork by team co-leader John Thornley, and 1 week of field activity each by the team members Janise Rodgers and Christopher Motter. The second phase of field

reconnaissance in spring and summer of 2019 comprised 2 weeks of fieldwork by each of the team co-leaders, Wael Hassan and John Thornley, while the third phase in September 2019 included 3 days of fieldwork by team co-leader Wael Hassan.

The EERI Reconnaissance Team collected a significant amount of valuable perishable damage data firsthand throughout the reconnaissance mission, which were used to establish a damage database by the team. In addition, the team was able to secure other valuable damage databases and inspection reports by several governmental and private organizations involved in damage assessment and repair in both the Anchorage and Mat-Su Boroughs. Data processing and report drafting started in Feb 2019 and continued through the end of 2019, submitting the draft report to EERI at the first anniversary of the earthquake in Nov 2019. The peer review and production processes amidst the pandemic situation further delayed the official release of the report to early 2021. The EERI Reconnaissance Team conducted exploratory studies on building damage patterns, resilience and recovery, instrumented buildings, schools and hospitals, and bridges and lifelines that appeared/will appear in subsequent journal publications.

1.4 Coordination with Other Reconnaissance Teams

The local EERI Learning from Earthquakes (LFE) co-leaders Wael Hassan and John Thornley provided assistance, contacts, coordination, access, and technical data to more than 16 different reconnaissance and inspection teams from December 2018 to September 2019. These teams include the Federal Emergency Management Agency; Applied Technology Council 20 local volunteers; Skidmore, Owings and Merrill, San Francisco; the University of Alaska, Anchorage; Simpson Gumpertz & Heger, San Francisco; the Electric Power Research Institute; the Municipality of Anchorage; Thornton Tomasetti, NSF-Structural Engineering Extreme Event Reconnaissance; Geotechnical Engineering Extreme Event Reconnaissance; the EERI Virtual Reconnaissance Team; the EERI Business Resilience Team; the Pacific Earthquake Engineering Research Center; the U.S. Geological Survey; the National Institute for Standards and Technology; and Acceptable Risk, LLC, California, besides several other individuals.

1.5 EERI Clearinghouse Coordination

Following the earthquake, EERI held 10 physical and virtual earthquake clearinghouses in Anchorage at Golder Associates through the end of January 2019. The clearinghouse notes can be found at <http://www.learningfromearthquakes.org/2018-11-30-anchorage-alaska/>. The first clearinghouses were held daily starting on December 1 for 5 days after the event then every 2 to 3 days until December 17. One more clearinghouse was held in January to follow up on the reconnaissance efforts after the holidays. The clearinghouses were very efficient in communicating and exchanging field reconnaissance data, reducing duplicate work, coordinating different teams' activities, securing building access for inspection, and focusing reconnaissance efforts on more perishable data sites/heavier damage sites. The clearinghouse notes are one of the sources the EERI Field Reconnaissance Team used to confirm and document some damage observations.

1.6 EERI and LFE Program

EERI was established in 1948. EERI is the leading nonprofit technical organization that connects those dedicated to reducing earthquake risk. The multidisciplinary membership includes engineers, geoscientists, social scientists, architects, planners, emergency managers, academics, students, and other like-minded professionals. The objective of EERI is to reduce earthquake risk by (1) advancing the science and practice of earthquake engineering; (2) improving understanding of the impact of earthquakes on the physical, social, economic, political, and cultural environment; and (3) advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes.

The EERI LFE program was established in 1973, with a mission to accelerate and increase learning from earthquake-induced disasters that affect the natural, built, social, and political environments worldwide. The mission is accomplished through field reconnaissance, data collection and archiving, and dissemination of lessons and opportunities for reducing earthquake losses and increasing community resilience. Through LFE, EERI sends multidisciplinary reconnaissance teams of earthquake-risk-mitigation experts to investigate earthquake impacts. Reconnaissance teams travel to earthquake-impacted areas, document important observations, and identify topics in need of follow-up research. Increasingly, LFE has focused on capturing lessons for community resilience through earthquake reconnaissance. LFE has developed a framework for resilience reconnaissance and has begun conducting follow-up reconnaissance trips months and years after damaging earthquakes. Volunteer EERI field teams are deployed on trips that aim to document impacts, identify knowledge

gaps for which further research is most needed, and identify practices that will improve mitigation measures, disaster preparedness, and emergency responses for future disasters.

1.7 Organization of the Report

This report is a multidisciplinary seismological and engineering report that is organized in 11 chapters plus bibliographical references and one appendix. The report is a first version that might be amended with subsequent versions and other independent publications should more information and lessons become available in the future. Besides this introduction in Chapter 1, Chapter 2 presents the tectonic setting and seismological aspects of Southcentral Alaska. Chapter 3 presents the geotechnical impacts of the earthquake on the region. Chapter 4 portrays the structural damage observed in buildings along with the performance of instrumented buildings in Anchorage. Chapter 5 comprehensively depicts the observed nonstructural systems and equipment damage in buildings. Chapter 6 is dedicated to the performance of schools during the earthquake and their earthquake resiliency. Chapter 7 focuses on the impact of the earthquake on hospitals. Chapter 8 presents the impacts of the earthquake on the transportation system, including bridge structures, in Southcentral Alaska. Chapter 9 discusses the impacts of the earthquake on lifelines and utilities. Chapter 10 was contributed by FEMA Region 10 to present their risk mitigation recommendations based on an independent Nov 30, 2018 earthquake investigation that was not associated with the EERI Field Reconnaissance Mission presented in this report. Finally, Chapter 11 presents the report's main conclusions, lessons learned, and recommendations and a vision to mitigate seismic hazard in Alaska on the basis of the results EERI Field Reconnaissance Mission presented in Chapters 1 through 9. Appendix A presents the findings of EERI's business resilience team investigation, which was also performed independently from EERI Field Reconnaissance Mission presented in this report.

2 SEISMOLOGY, GROUND MOTIONS, AND AFTERSHOCKS

2.1 Topography and Geology

Southcentral Alaska, including Anchorage, Eagle River, Wasilla, and Palmer, is home to approximately half of Alaska's population and is located within a highly seismogenic zone. This zone is composed of the Pacific plate underthrusting the North American plate at a rate of greater than 50 mm per year (Figure 2.1). Anchorage is situated in a region of complex geology that consists of a sedimentary basin abutting metamorphic bedrocks exposed in the Chugach mountains, located on the eastern side of the city. One of the most important features affecting the ground response in Anchorage is the Bootlegger Cove formation, consisting of glacial and glaciofluvial deposits of interbedded clay, silt, and sand (Schmoll and Dobrovolsky, 1972).¹ Significant ground loss and slope failures within this formation resulted in the northern portion of the city during the 1964 Great Alaska Earthquake (Mw 9.2).

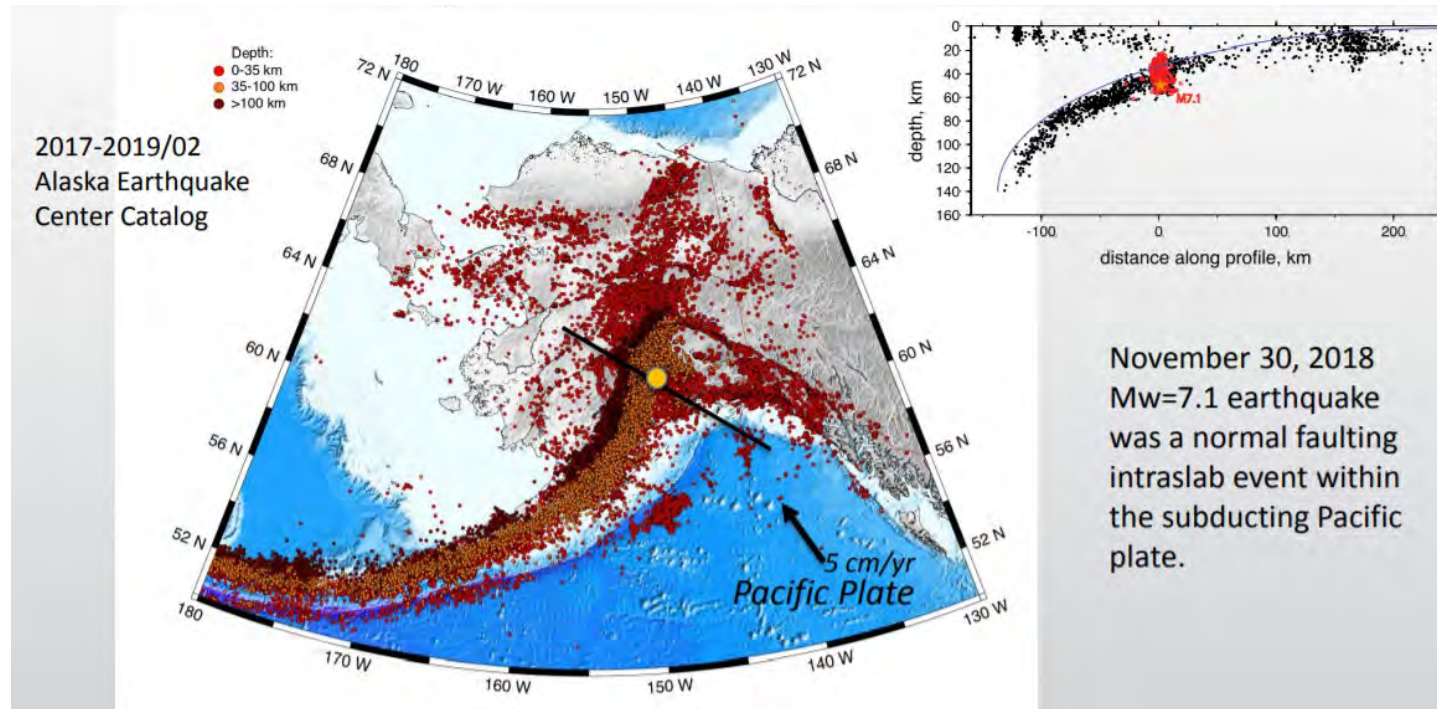


Figure 2.1. The November 2018 earthquake was a normal faulting intraslab event within the subduction Pacific plate (source: 2017–2019/02 AEC Catalog).

2.2 Southcentral Alaska Tectonics and Seismicity

On the morning of November 30, 2018, many families within Southcentral Alaska had dropped off or were in the process of dropping off children at school and going to work at 8:00 a.m. At 8:29 a.m., the Mw 7.1 Anchorage Earthquake struck the most populous region of Alaska, where more than half of Alaska's population resides. Initially the earthquake was estimated at an Mw of 7.0, but over the next several weeks was subsequently modified to an Mw of 7.1 after further review of the available data collected from the event.

Southcentral Alaska is located at the margin of the megathrust zone created by the Pacific plate subducting under the North American plate. Based on the U.S. Geological Survey (USGS) Slab 2.0 model (Hayes, 2018),² the Pacific plate is approximately 30–40 km below Anchorage and the surrounding communities and is dipping to the northwest. The main earthquake was located at a depth of approximately 46 km, and the epicenter was identified at 61.346°N, 149.955°W (USGS, 2019a³; Figure 2.2). The earthquake was approximately 12 km north of Anchorage and 19 km west of Eagle River. The main event was a normal faulting intraslab event within the subduction Pacific plate.

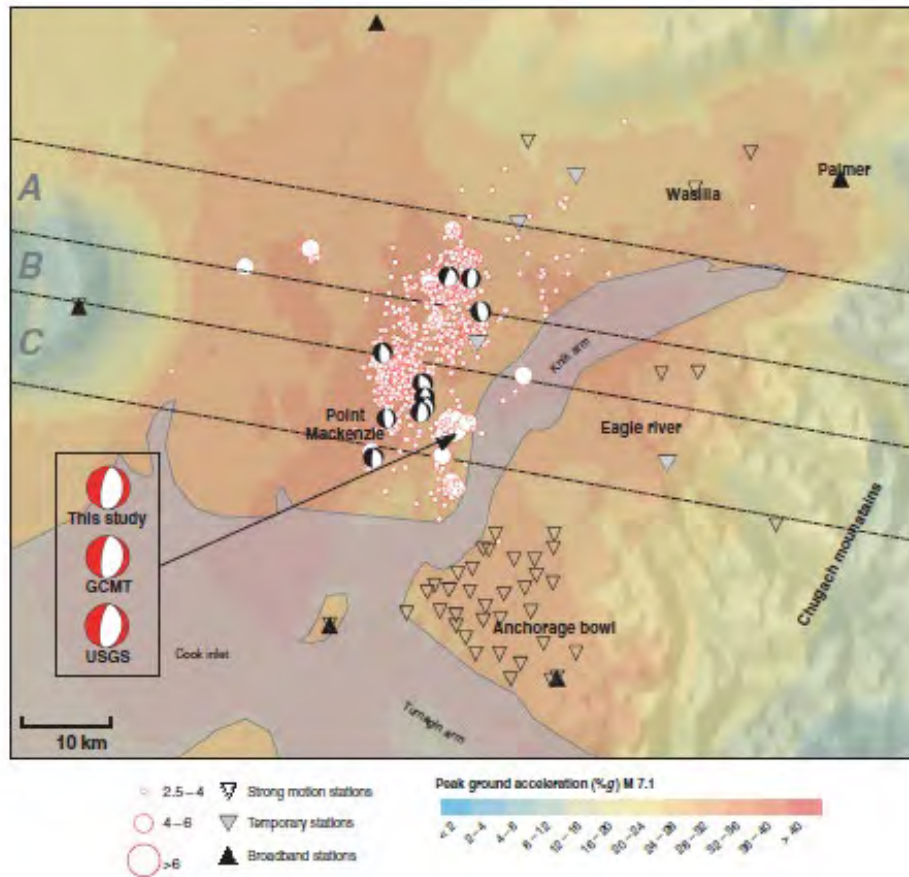
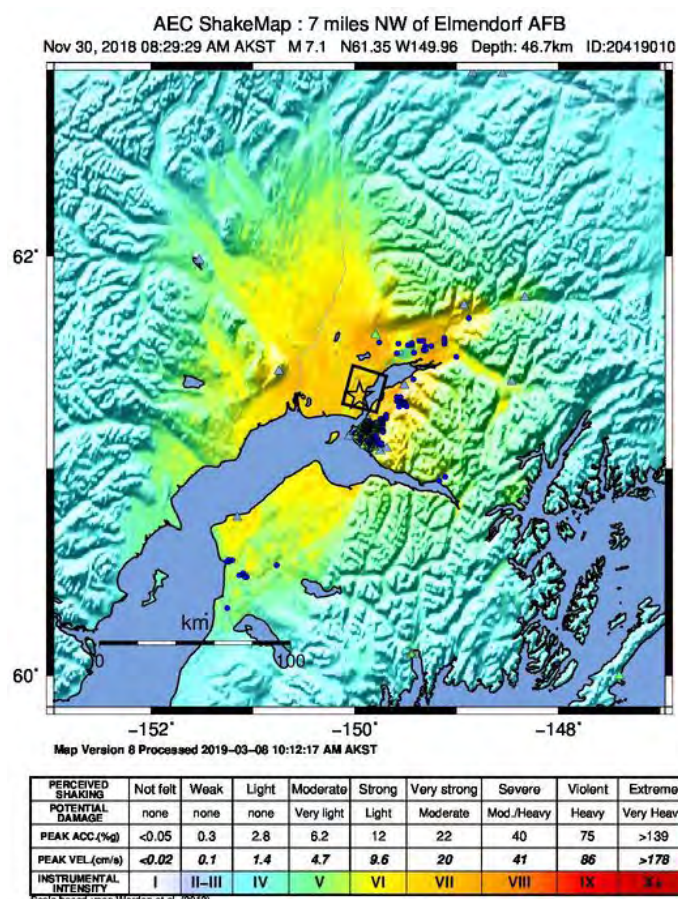
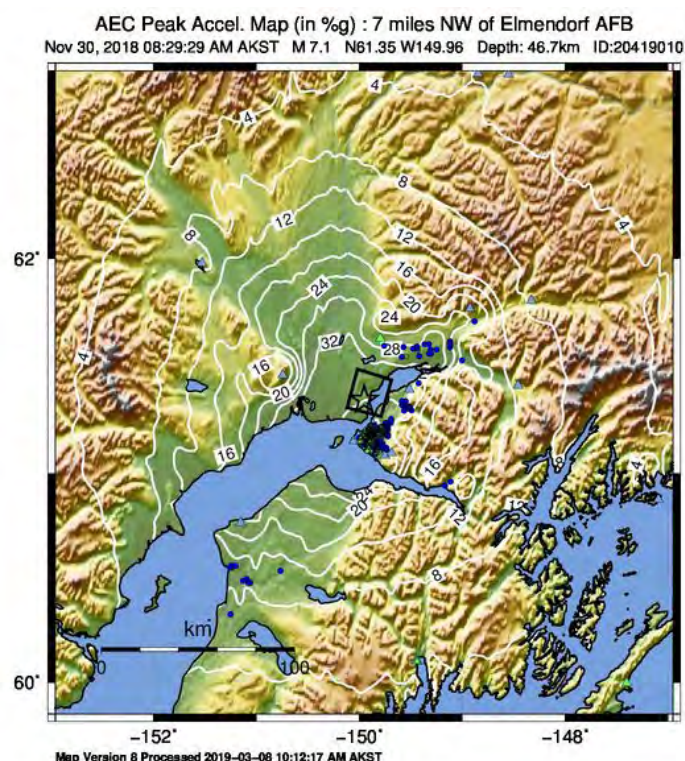


Figure 2.2. Main shock epicenter with regional PGA contours. Aftershock locations are shown in red. Strong-motion and broadband seismic stations locations are keyed to the legend (source: West et al., 2020⁴).

Figure 2.3 presents the Intensity ShakeMap developed by the Alaska Earthquake Center (AEC) (2019)⁵ for the main event. The data provided by the Center for Engineering Strong Motion Data (2019)⁶ provides data from 36 stations within 50 km of the epicenter. The recordings within 50 km indicate the maximum peak ground acceleration (PGA) recorded at a strong-motion station was 0.56g at the Rabbit Creek Fire Station (K215) station. A maximum PGA of 0.44g and a peak ground velocity (PGV) of 37 cm/s were measured at the ground station located at the Port Access Bridge, less than 14 km from the epicenter. Average values of PGA and PGV across Anchorage were 0.3g and 25 cm/s, respectively. The main event had a significant duration of approximately 15–20 seconds, based on review of strong-motion records.



(a)



(b)

Figure 2.3. (a) Intensity ShakeMap and (b) PGA contour map (source: AEC, 2019).

Additional information regarding the tectonics and seismicity can be found in West et al. (2020)⁷ and a Geotechnical Extreme Event Reconnaissance (GEER) report (Franke and Koehler, 2019).⁸

2.3 Historical Context: The M9.2 Alaska Earthquake

The November 30, 2018, earthquake was the strongest earthquake to affect the population of Southcentral Alaska since the 1964 Great Alaska Earthquake. It is also considered the strongest earthquake close to centers of population in the United States in the last 50 years. The November event was an intraslab event located in the subducting Pacific plate, while the Great Alaska Earthquake was an interface event. The rupture area of the November 2018 earthquake has been estimated to rupture for 12 seconds (USGS, 2019b).⁹ The 1964 megathrust event was not recorded by any local instrumentation. The depth of the 1964 event was estimated at 25 km, and it was epicentered 125 km east of Anchorage. The nearest seismograph stations were located in Fairbanks and Sitka, Alaska, in 1964. However, the duration of the 1964 earthquake shaking was estimated to last more than 4 minutes (USGS, 2019a), and the massive ground failures in Anchorage did not begin until a couple minutes into the shaking. As discussed later, none of the large slope-failure areas in Anchorage that had failed in 1964 were reactivated in 2018. There were also more than 130 deaths associated with the 1964 event, but only minor injuries have been associated with the 2018 event. This is especially interesting, as the population of Southcentral Alaska was less than 100,000 in 1960, swelling to a population of more than 400,000 in 2018 (Alaska Department of Labor, 2019).¹⁰ Major earthquake damage and tsunami-related damage resulted from the 1964 event (Figure 2.4).

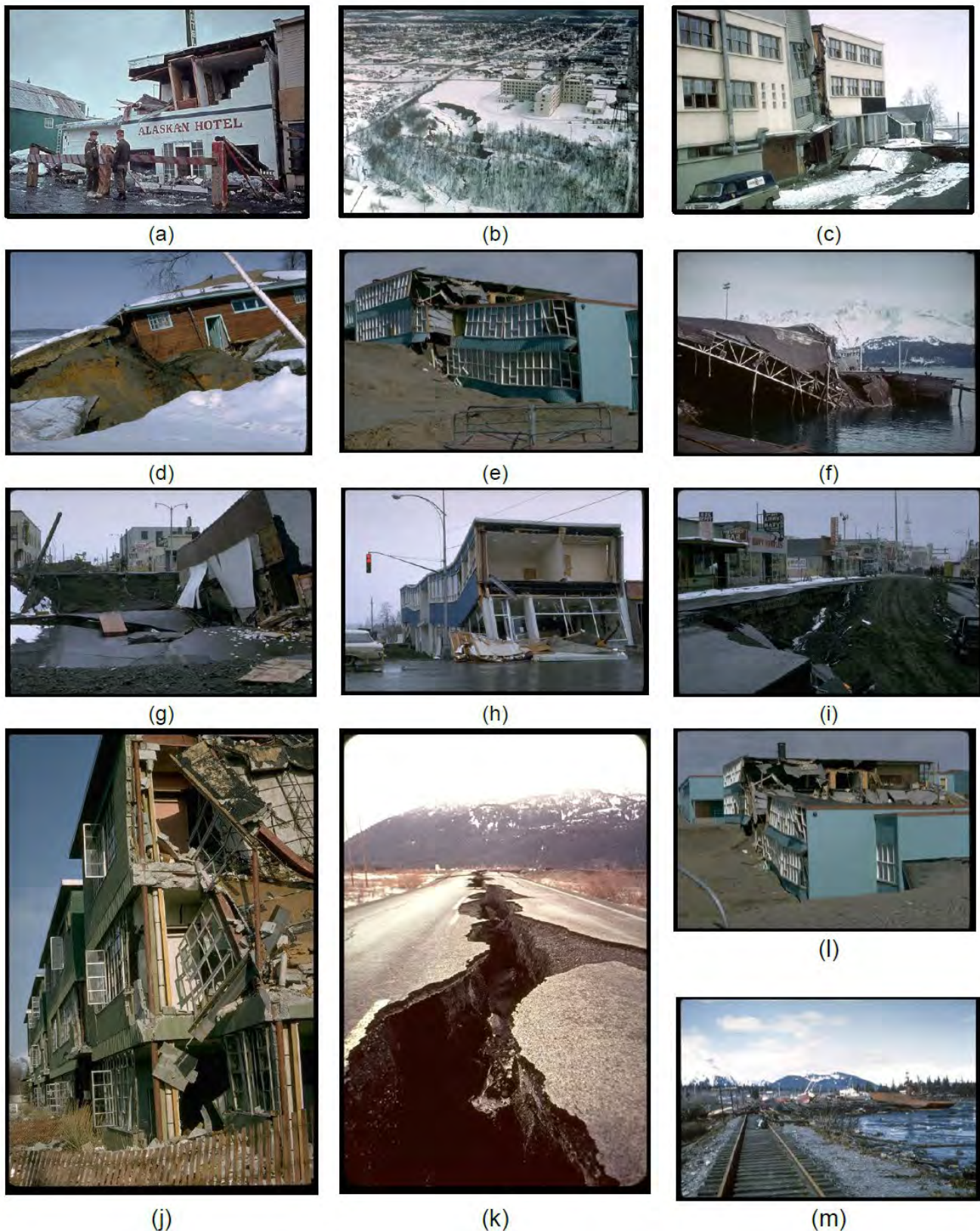


Figure 2.4. Major damage resulted from the 1964 M9.2 Earthquake (source: Mosalam et al., 2018⁴⁴; National Information Service of Earthquake Engineering NISEE).

2.4 Instrumentation of Anchorage Bowl and the November 2018 Anchorage Earthquake

Over the past several decades, a strong-motion network has been developed within Anchorage (Figure 2.5). More than 30 strong-motion stations are located in the free field, and 8 structures have been heavily instrumented. The recordings from

the strong-motion stations have been used to estimate the variability of site response across Anchorage. The following figures (Figures 2.6, 2.7, 2.8, and 2.9) present the estimated PGA, PGV, and spectral accelerations at 0.2-second and 1.0-second periods, respectively. The figures were developed by Dr. Utpal Dutta of the University of Alaska, Anchorage (UAA); John Thornley of Golder Associates and the University of Strathclyde, Glasgow; Muhammad Saif Uddin of UAA; Dr. Joey Yang of UAA; and Andy Garrigus of Golder Associates. These maps were provided to assist field teams, especially during the period when the USGS was furloughed because of the 2018 U.S. government shutdown. The data is also being used by Federal Emergency Management Agency and municipality of Anchorage Building Safety to better understand the damage observed within Anchorage and Eagle River.

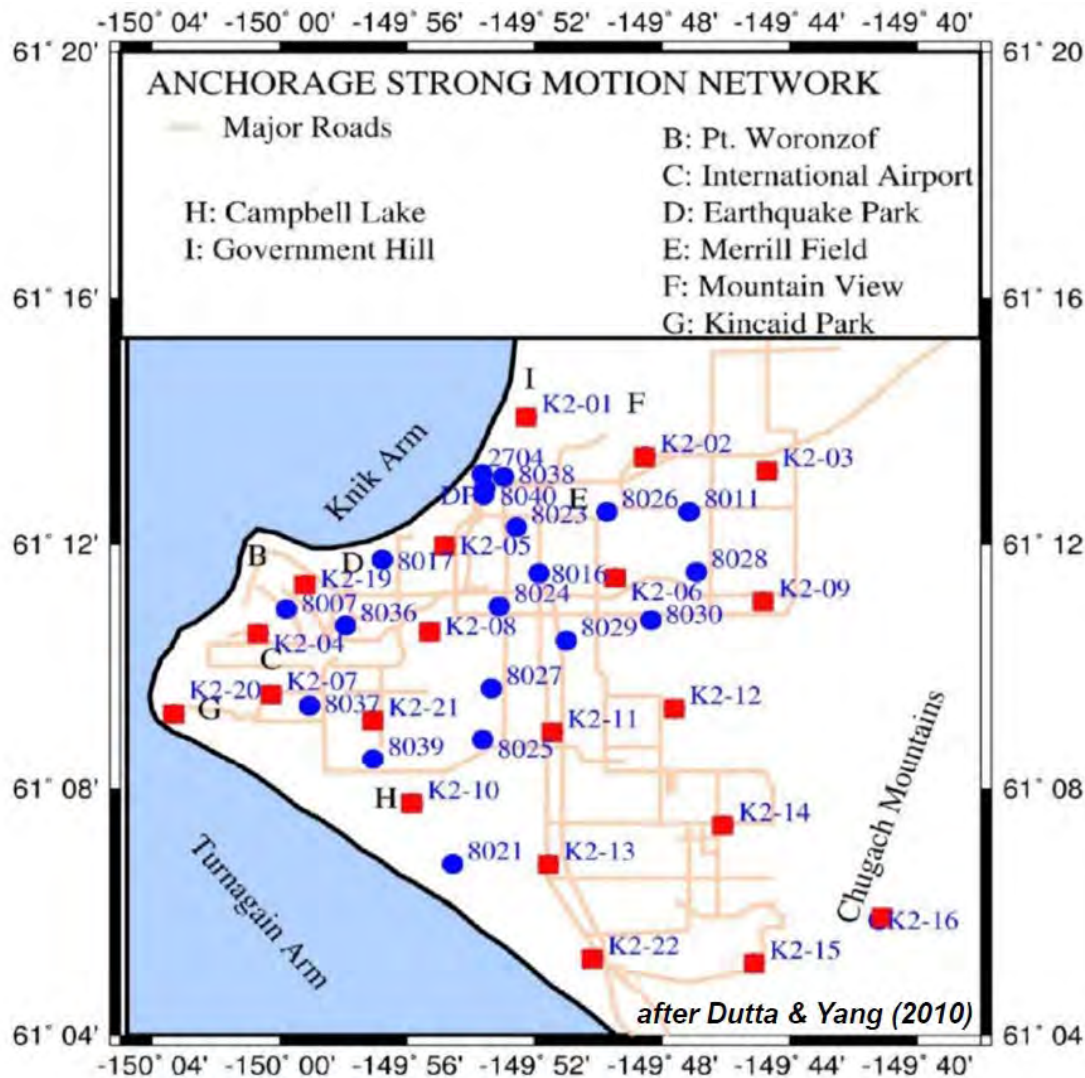
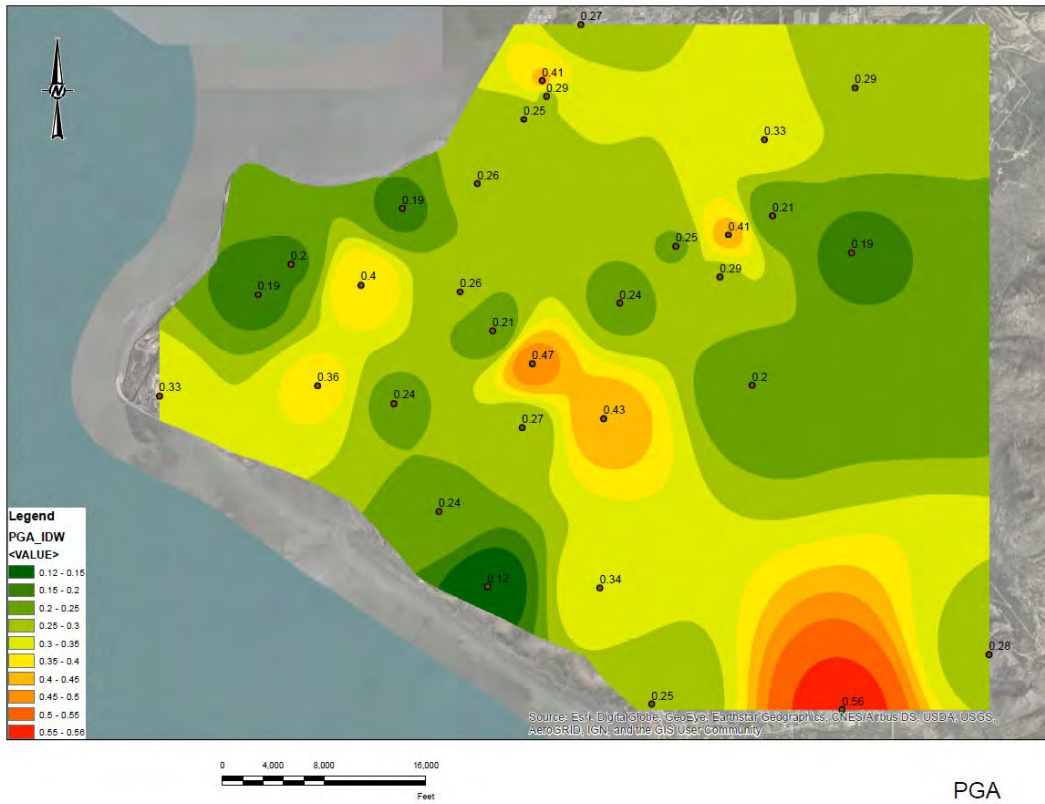
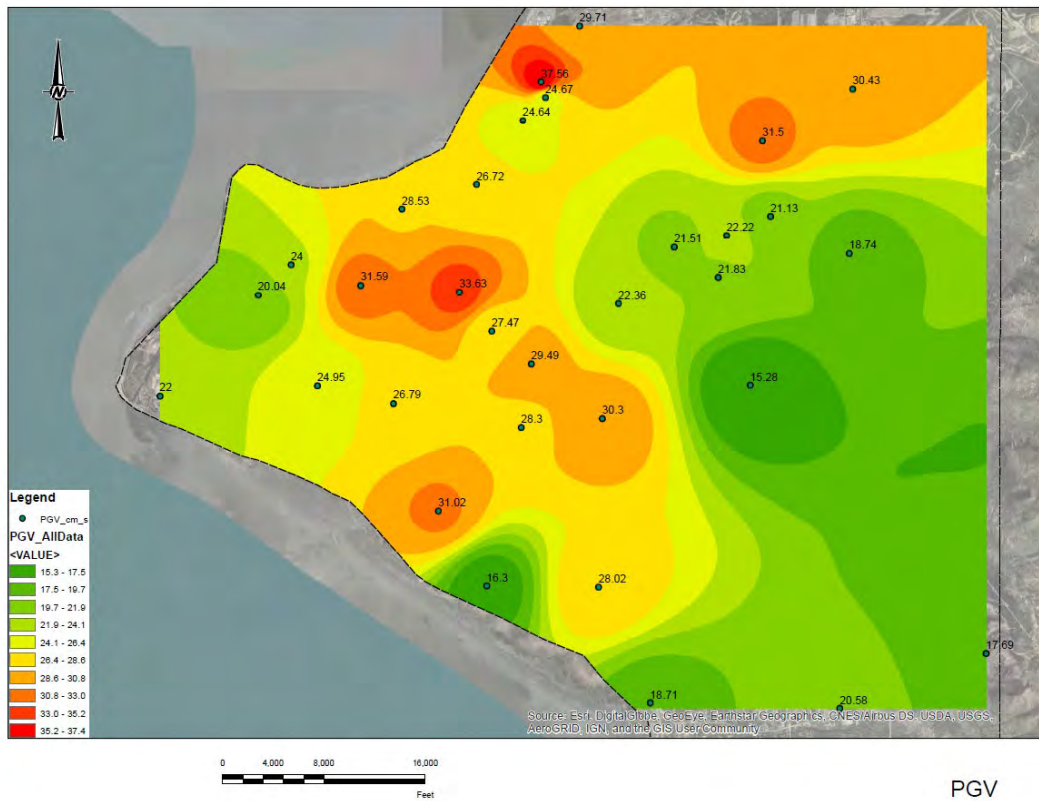


Figure 2.5. Strong motion seismic instrumentation network in Anchorage Bowl (Dutta et al., 2010).¹²



PGA

Figure 2.6. PGA map of Anchorage (source: Dutta et al.).



PGV

Figure 2.7. PGV map of Anchorage (source: Dutta et al.).

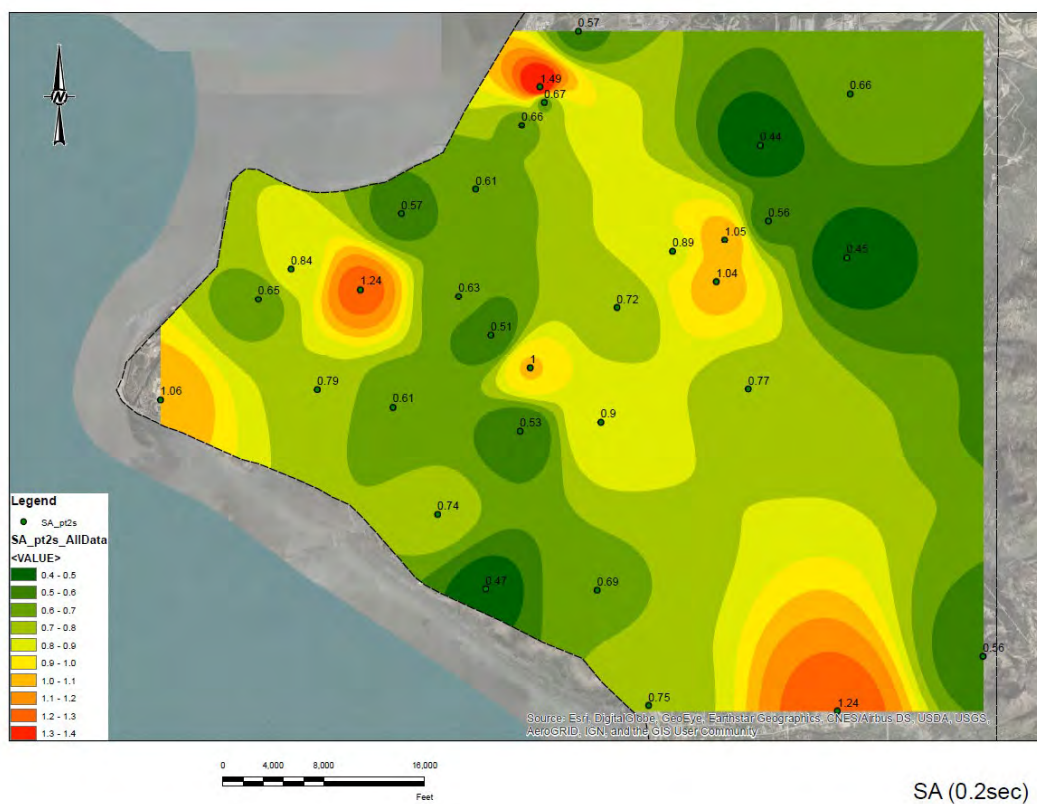


Figure 2.8. Spectral acceleration (0.2-second) map of Anchorage (source: Dutta et al.).

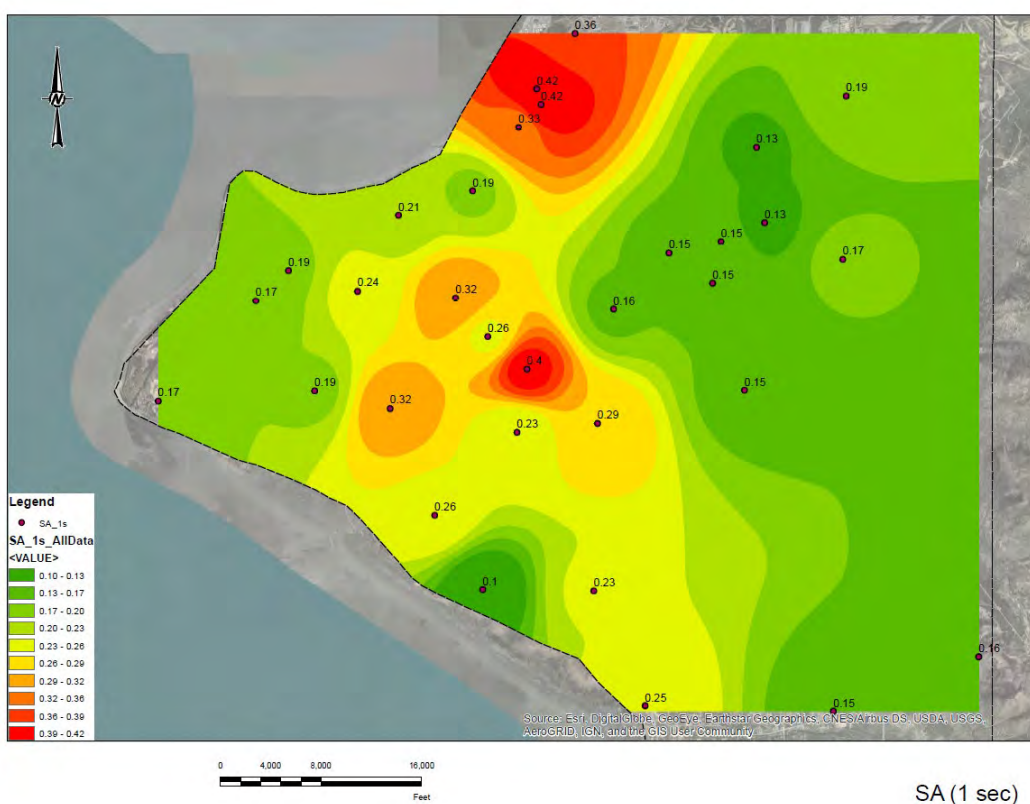


Figure 2.9. Spectral acceleration (1.0-second) map of Anchorage (source: Dutta et al.).

Examples of the calculated response spectra from measured ground motions at several stations are presented below. The design response spectra modified for the seismic site class are also presented. National Strong Motion Program (NSMP)

Station 8030, located at Anchorage Police Headquarters on the east side of Anchorage is presented in Figure 2.10. The 5%-damped response spectra for the three recorded components, east-west (HNE), north-south (HNN), and vertical (HNZ), are plotted in the figure. The processing and calculations were performed by Dr. Utpal Dutta and John Thornley using data provided by AEC and Seismic Analysis Code and MATLAB code. Site response analysis of the data was presented by Dutta et al. (2019) at the 2019 Annual Meeting of the Seismological Society of America.

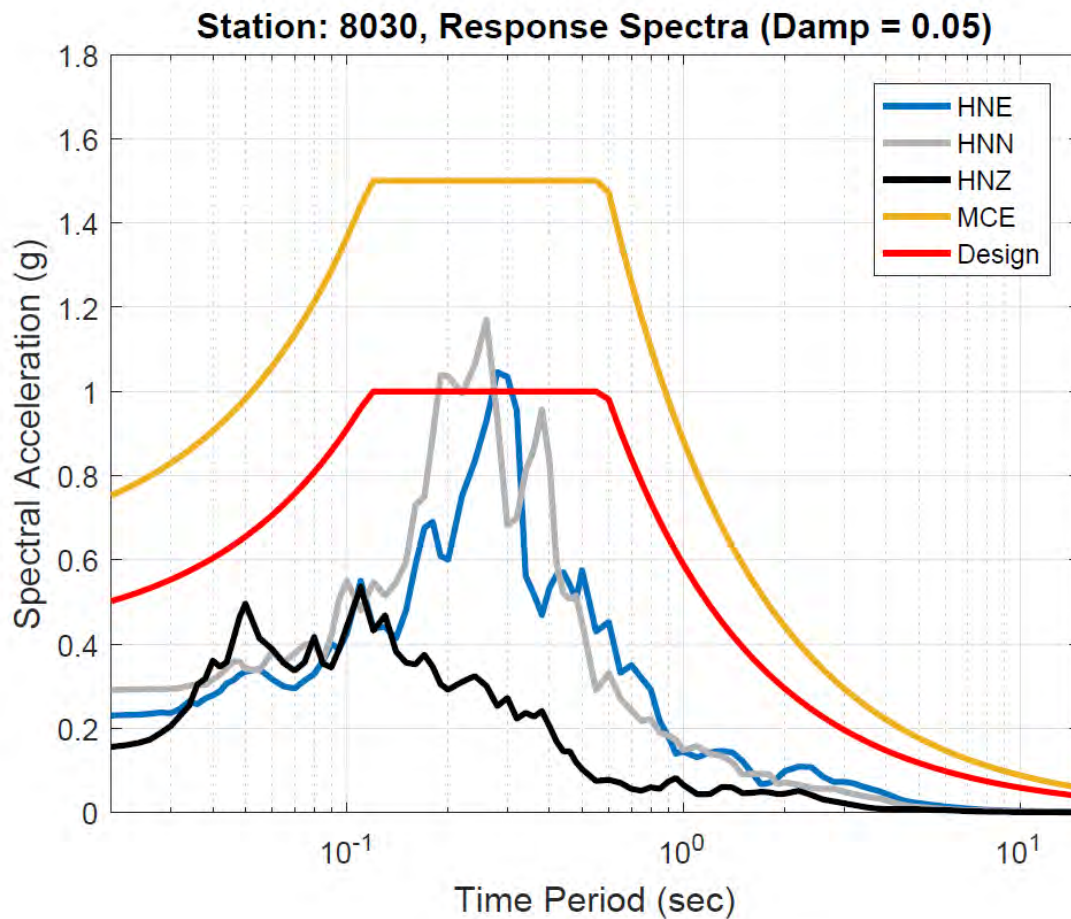


Figure 2.10. NSMP Station 8030, Anchorage Police Headquarters (Dutta et al.).

At NSMP Station 8036, U.S. Department of the Interior Office of Aviation Services, the HNZ has significantly higher spectral accelerations when compared to NSMP Station 8030. Both horizontal components (HNE and HNN) indicate higher spectral accelerations as well (Figure 2.11). Some damage occurred near NSMP Station 8036, including damage to an aircraft hangar, roadways, and other infrastructure. The GEER team also indicates in their report that analysis of the time history data indicates the possibility of liquefaction to have occurred at the site (Franke and Koehler (Eds.), et al., 2019).

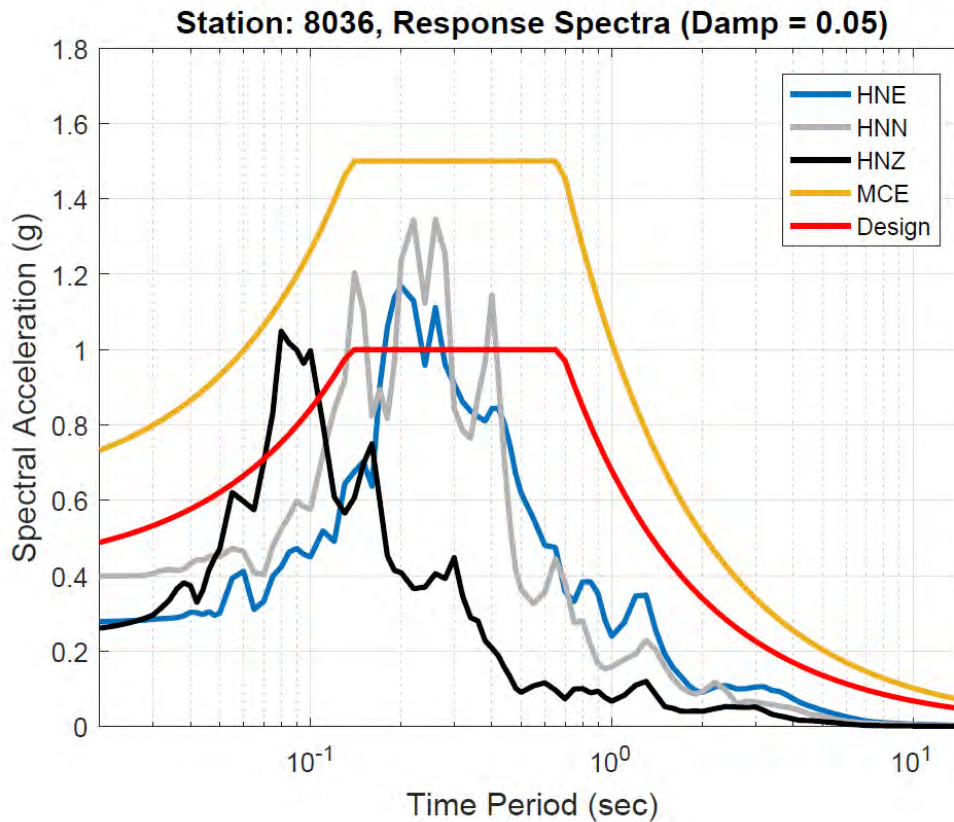


Figure 2.11. NSMP Station 8036, U.S. Department of the Interior Office of Aviation Services (Dutta et al.).

2.5 Aftershock Sequence

Numerous aftershocks have been felt by residents of Southcentral Alaska. From November 30, 2018, through August 2019 more than 10,000 aftershocks have been recorded (AEC, 2019). Only 50 of those aftershocks have been Mw4 and greater; the last recorded was August 28, 2019. There have been seven aftershocks with magnitudes between Mw5.0 and Mw5.7, and those events occurred within 45 days of the main event (the last was January 13, 2019). There were 80 aftershocks the first day (November 30), 3 of which were larger than Mw5.0. The first strong aftershock was Mw5.8 at 8:35 a.m., only 6 minutes following the main event. The CESMD has posted processed earthquake data for the main event and many of the Mw4.0 and larger events. Figure 2.12 shows the aftershock sequence from November 30, 2018, until September 2019. Ruppert et al.¹³ estimate that the aftershock sequence will continue for 2.5 years following the main event.

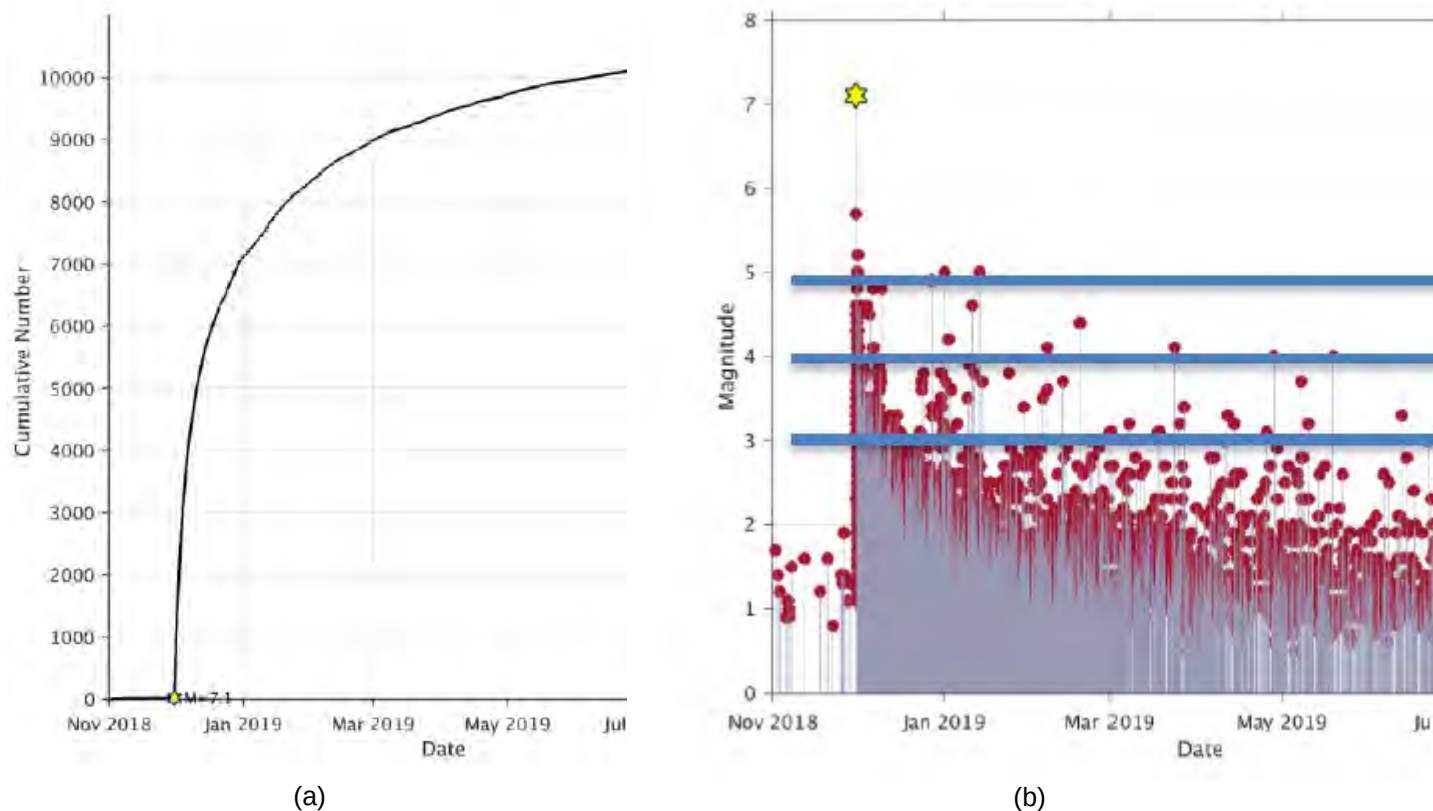


Figure 2.12. Cumulative aftershock (a) number and (b) magnitudes for 10 months following the main event (source: Ruppert et al. 2019).

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3 GEOTECHNICAL IMPACTS

3.1 Introduction

As noted, the November 30, 2018, Mw 7.1 earthquake and subsequent aftershocks are considered by many engineers and seismologists as lower than the considered design-level earthquake. The resulting damage, while widespread, was typically considered to be nonstructural, resulting in cosmetic repairs. However, one interesting note by many structural engineers evaluating commercial and residential structural damage was that damage to structures seemed to be more often related to geotechnical failures, such as ground subsidence, slope failures, and liquefaction. The following sections provide some detail related to the types of geotechnical failures observed. The following sections are not aimed at providing a comprehensive list of observations or thorough explanations of the observed failures. Those efforts can be found in reports by others including the Geotechnical Extreme Event Reconnaissance (GEER) group (Franke and Koehler, 2019¹) and others. Numerous public and private efforts related to the evaluation and recovery efforts will provide valuable data in the months and years to come.

3.2 Liquefaction

There were observations of liquefaction and liquefaction-related damage across Anchorage and Southcentral Alaska. The following are some highlights of the observations collected. The GEER report (Franke and Koehler, 2019) provides extensive information on this topic.

3.2.1 Free-Field Observations

During the first days of observations, performed by the U.S. Geological Survey (USGS) and other reconnaissance teams, signs of liquefaction were noted in tidal lowlands around the Cook Inlet, where sand boils were apparent (Witter and Bender, 2018).² Numerous observations were noted across Southcentral Alaska.

3.2.2 Port of Alaska

The Port of Alaska, which is responsible for receiving a majority of Alaska's goods and fuel, sustained some damage related to the earthquake. The main port trestle and wharf structures were constructed in 1961 and performed well during the 1964 Great Alaska Earthquake (USGS, 2019a). However, the port's pile-supported structure has suffered in recent years because of significant corrosion of the steel piling. In the days following the 2018 earthquake, the major icing on the piles made damage difficult to observe. In the spring, several studies were conducted, and damaged piles were observed. The damages included failures of the welds of spiral-welded piles near the mud line, where corrosion is typically worst.

Several cracks were noted at the crest of the shoreline, which are attributed to lateral spreading. Sand boils were also observed (Franke and Koehler, 2019). A port upgrade project was under construction for a new terminal at the time of the earthquake. Ground improvements for the shoreline had been performed earlier in 2018. The cracking at the crest of the shoreline was observed on the slopes adjacent to the ground improvements, but no displacements or cracking were observed within the slopes that had received ground-improvement treatments.

3.2.3 Transportation Infrastructure

Liquefaction-induced settlement of roadways was not common but did occur in parts of Anchorage and outlying areas. An example of the damage resulting from liquefaction included portions of the Seward Highway north of East Tudor Road. Both the northbound and southbound lanes settled differentially by several inches and were closed to traffic for safety. In the days following the earthquake, the Alaska Department of Transportation and Public Facilities (ADOT&PF) was able to work with a contractor to remove distressed pavement, level the subgrade, and repave the affected lanes as a temporary measure. Additional repairs will be performed for a permanent solution, as the affected areas have continued to settle after the spring thaw and still have uneven driving lanes.

3.2.4 Residential Structures

Residential structures within the municipality of Anchorage (MOA), especially those within the middle to western portions of the city, were affected by liquefaction-induced damages. Several neighborhoods were affected where fine sand ejecta was visible in the streets, settlement of yards was visible around homes, and crawl spaces were filled with fine sand.

Crawl spaces below the ground level floor of residential structures are common within Southcentral Alaska. In areas affected by liquefaction, numerous homeowners found fine sand had filled portions of crawl spaces (Figure 3.1). In other homes where basement floors consisted of a concrete slab on grade construction, fine sand was found to have come through the joints (Figure 3.2) at the edge of the floor slab, and obvious settlement of the concrete slab was observed (Figure 3.3). Settlement of shallow foundations was also observed, and door and window openings were askew. Utility services, especially for gravity-fed sewer lines, were also impacted, and repairs were required to reestablish proper flow direction (Figure 3.4).



Figure 3.1. Liquefaction sand ejecta in residential crawl space (photo: Howard Weston).



Figure 3.2. Slab on grade liquefaction ejecta (photo: Howard Weston).



Figure 3.3. Slab on grade liquefaction-induced settlement of 6 cm (photo: Howard Weston).



Figure 3.4. Displaced residential sewer service (photo: Howard Weston).

3.2.5 Commercial Structures

Commercial structures also suffered from similar damages. Liquefaction-induced settlement was observed at several buildings. Further analysis of these damages is being performed by the engineering community, and findings from these studies will provide additional insight into a variety of construction techniques and the impacts on commercial structures.

3.3 Lateral Spreading

There were several cases of lateral spreading observed following the earthquake. As noted previously, minor lateral spreading was observed at the Port of Alaska shoreline. A parking area at a local business park also suffered from minor movements attributed to lateral spreading. The subsurface soils consisted of loose, poorly compacted soils that were placed to fill in a historic gravel pit with high groundwater. The lateral spreading observations for several sites are presented in the GEER report (Franke and Koehler, 2019).

3.4 Slope Failures

Several significant slope failures occurred as a result of the earthquake. Observations following the November event indicated that major slope failures from the 1964 Great Alaska Earthquake did not remobilize (Jibson et al. 2020³). The relatively short duration of shaking, when compared to the 1964 earthquake, is thought to be one reason these slopes did not remobilize. However, several other slope failures were observed and documented. Notable slope failures included the slopes near milepost 24 on the Glenn Highway near Mirror Lake, near milepost 50 of the Seward Highway, and near the Alaska Railroad Corporation tracks near Rabbit Creek in south Anchorage (Franke and Koehler, 2019).

As noted earlier, at the time of the earthquake, there were about 0.3–0.5 m of seasonally frozen ground, which can behave as a stiff crust over the thawed soils below. In the months following the earthquake, observations along road embankments have found cracks parallel to the crest of embankment slopes, which in many cases are in line with guardrails. The cracks in the embankment are typically at the edge of the pavement and range from less than an inch to several inches wide, with depths of 0.3 m up to 1 m in some cases. Many of these cracked embankments do not show vertical displacement and are primarily horizontal. In some instances, the near-surface slides damaged culverts.

As spring thawed out the frozen soils, there were several embankments that slumped, causing pavement damage and roadway settlement. These damages, while occurring several months after the earthquake, are attributed to frozen soils that lose the bridging effect once thawed.

3.5 Subsidence

Numerous peat bogs have been developed over the years, some for commercial use and some for residential neighborhoods. A common practice is to excavate the peat from below the structures, from below the roads, and within utility trenches but perform only minor mitigation of the peat for yards, driveways, and open areas. While it is common in these neighborhoods to find repairs to the driveways to reestablish access into garages, it was observed that greater settlement had occurred as a result of the earthquake, and numerous homes had stacked dimensional lumber in front of garages because of the differential settlement of driveways compared to the home (Figure 3.5). Water valves were also found to protrude from the ground surface because of settlement of the soils and peat around the valve. In some instances, the residential sewer connections had settlement and needed repairs because of poor soils below the service.



Figure 3.5. Driveway settlement at a residential driveway (photo: Howard Weston).

3.6 Foundation Soil Failure

Some of the larger failures that were observed consisted of native foundation soils that failed below fill soils. Two examples of this, which received national and international attention in the days following the earthquake, include the Minnesota Drive northbound offramp at International Airport Road in Anchorage and Vine Road in Wasilla (Figure 3.6). Both sites included constructed road embankments over soft soils. While both sites are being studied to understand

failure mechanisms, it appears that in both cases the foundation soils failed and caused rotational failures of the overlying embankments.



Figure 3.6. Vine Road failure (photo: Earthquake Engineering Research Institute (EERI) Clearinghouse).

The Minnesota Drive offramp is constructed in an area where groundwater is near the surface and peat soils overlie fine-grained sandy silt, which tends to be soft near the ground surface (Schmoll and Dobrovlny, 1972⁴). The initial failure mode is assumed to be global rotational slope failure due to low-shear-strength, saturated, sandy silt soils unable to resist the driving forces of the roadway embankment fill above.

Because of the glacial terrain consisting of ridges of glacial till comprising silt, sand, and gravel and valleys with deep peat or muskeg found across Southcentral Alaska, road construction can be challenging. The muskeg is often found to be greater than 3 m deep, and surcharging is a common practice in lieu of overexcavation. Vine Road, at the location of the failure, crosses deep muskeg. Observations suggest the failure is again likely due to global rotational slope failure caused by saturated low-shear-strength peats supporting the road embankment. This site will be interesting for further study because there are numerous roads that are constructed in similar conditions that did not fail because of the Anchorage earthquake.

3.7 Anthropogenic Fill Failures

During the days following the earthquake, numerous groups in the field, as part of several reconnaissance teams observed failures that appeared to be due, in part, to anthropogenic fill soils below structures (Franke and Koehler, 2019; EERI Clearinghouse). Differential subsidence of fills caused impacts to numerous structures, including residential buildings (Figure 3.7). There were observations of fill slopes becoming unstable above other residential structures, causing red tagging of homes because of potential slope failures. As the aftershocks continued in the days and weeks after the main event, numerous building owners were concerned about the safety of these structures and the poor fill materials.



Figure 3.7. Anthropogenic fill failure (photo: EERI Clearinghouse).

3.8 Resiliency of Transportation Infrastructure

In the hours following the earthquake, several roads were closed because of damage. The damage to ADOT&PF roads was related to rock fall, south of Anchorage on the Seward Highway; embankment foundation failures at Vine Road and

the Minnesota northbound off ramp; and bridge approach settlement on Glenn Highway, north of Anchorage, among others. Using the average annual daily traffic (AADT) data available from ADOT&PF (2019a)⁵ and the earthquake updates following the November 30 event posted by ADOT&PF (2019b),⁶ a resiliency curve was developed on roads that were closed because of earthquake damage.

The quick response by the AKDOT&PF was due in part to several aspects. These included the time of year, contractor relationships, and weather (EERI, 2019).⁷ Many of the construction staff were in the office performing project closeout and follow-up activities from the summer construction season and were paused in that effort and available to support recovery efforts. Relationships with contractors allowed ADOT&PF staff to get contractors into the field quickly and work through contracting while recovery work was being performed. In addition, there was very little snow at the time of the earthquake, and the frost was only 0.3–0.5 m deep. This allowed contractors to open stockpiles of aggregates and use thawed material in the backfilling of temporary repairs. The asphalt hotplants were also reopened, and, for a short period of time, paving was able to be performed.

Figure 3.8 details the resiliency related to the ADOT&PF road closures. The percentage of AADT impacted by these road closures was used to estimate the impact to the public. As can be seen, there was a significant improvement for the public on December 4, 2018, which corresponds to several roads reopening. Nine days after the earthquake, all closed roads were opened. With the initial closures, an estimated 240,000 AADTs were impacted, not including the roads where damage required repairs, but including roads that remained passable.

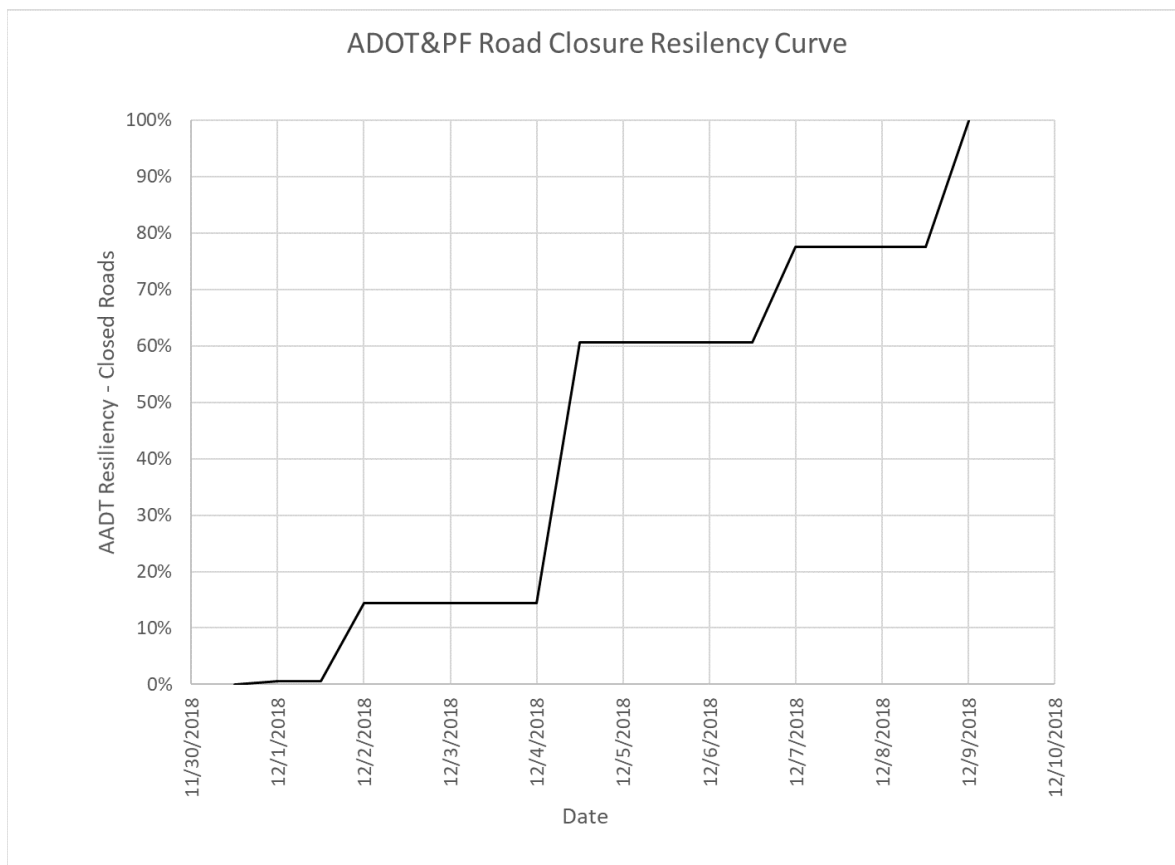


Figure 3.8. ADOT&PF road closure resiliency curve, annual average daily traffic (AADT) (source: ADOT&PF, 2019a).

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3.9 Damages to Structures

One resulting discussion related to the earthquake is related to the effectiveness of the current building code. In the MOA, the current building codes include the 2012 versions of the International Code Council code (i.e., the 2012 *International Building Code (IBC)*, 2012 *International Residential Code (IRC)*, etc.), with local amendments. In Palmer, the building codes adopted were the 2015 IBC and 2015 IRC. Outside of these two service areas, the state of Alaska is the jurisdiction responsible for building codes. At the time of the earthquake, the state of Alaska had adopted the 2012 IBC. The State Fire Marshall's Office and the Department of Labor share in the oversight of the application of the code in the areas outside of Anchorage and Palmer.

Within the MOA, there are two regions related to building oversight. Construction within the MOA Building Safety Service Area (ABSSA) is required to follow a more regulated process, including the application and approval of a land-use permit and building permit. This applies to both residential and commercial construction. As part of the process, developers submit plans for review and approval prior to construction, and then the municipality performs inspection services during construction to verify compliance with approved plans. This activity has been strongly enforced since the early 1990s, offering nearly three decades of oversight to construction within the ABSSA.

Outside of the ABSSA, in areas such as Eagle River, construction is only required to apply for and receive a land-use permit. Plans for residential construction are not required to be reviewed by any agency. Commercial construction outside the ABSSA, but within the MOA, are required to have a plan review by the State Fire Marshall's office, where life safety issues are reviewed, but no structural review is specifically performed. This is also true for other construction that is within the jurisdiction of the state of Alaska.

There have been several efforts over the years to incorporate the entire MOA within the ABSSA. However, there has been a desire by those outside the ABSSA to keep "regulation" to a minimum. While all residential and commercial construction within the MOA but outside the ABSSA can apply for permits that include plan review and inspections, only a small percentage do (R. Noffsinger, *pers. comm.*, 2019). As part of an effort to understand the potential impacts of the code on construction (i.e., effectiveness of code for building safety) the MOA, Federal Emergency Management Agency, and others have collected the data related to self-reported building damage notices within the municipality (Askov, 2019). This work is ongoing at the time of publication of this report. More discussion on the history and application of building codes in the regions is detailed in Chapter 4 of this report.

3.10 Utilities

The Anchorage Water and Wastewater Utility (AWWU) immediately received notifications that parts of the water and wastewater systems within Anchorage had been damaged as a result of the earthquake. As a result of some of the breaks, a boil-water notice was posted, and alerts went out to the community over a variety of media sources. The boil alert was in effect for several days after the earthquake and was lifted once integrity of the water system could be verified. Very few residents on municipal water were affected, and most were residential customers. Repairs began immediately. Typically, the utility anticipates some sewer and water line breaks in an average year. This metric will help AWWU estimate the number of breaks that were potentially related to the earthquake over the next year. The GEER report (Franke and Koehler, 2019) has detailed specifics related to the type of sewer and water line materials that were used by AWWU and were affected. Further analysis, including resiliency evaluations, will be produced in future publications.

While much of the damage was related to buried utilities, AWWU did have some minor facility damage. This damage included minor stairwell and façade cracking and a glycol leak at the main headquarters. At several of the water and wastewater treatment facilities, there were observations of pipe leaks. However, in general, operations of the utility returned to normal operations within several hours of the earthquake.

3.11 Wells and Groundwater

**By: Cara Shonsey
Golder**

Consideration of the impacts on groundwater and wells in Alaska from a seismic event is important because a significant portion of the state's fresh water supply is produced from groundwater sources. Based on estimates from 2010 by the USGS (2014)⁸, freshwater produced from groundwater accounts for the following percentages of Alaska's use: 55% of Alaska's total supply, 34% of total public supply, and 95% of individual household supply. The above estimate for public supply that is produced by a groundwater source does not account for public water that incorporates groundwater for supplementation and redundancy of surface-water supply, such as the MOA and Juneau, Alaska; therefore, the percentage is considered to be higher than 34% (C. Palmer, *pers. comm.*, 2019).

The majority of residents in the Southcentral Alaskan communities that experienced higher-intensity ground shaking during the 2018 Anchorage Earthquake (e.g., Eagle River, Palmer, and Wasilla, etc.) primarily use water produced from a groundwater supply. The exception is the MOA, which is serviced by the AWWU. An estimated 240,000 people, or approximately 80% of the resident population, are serviced by the AWWU (AWWU, 2019)⁹ when compared to the 2018 population estimates by the State of Alaska Department of Labor (2019). The majority of the water provided by the AWWU is from the surface-water supply of Eklutna Lake. In the MOA, the remaining 20% of residents are serviced by on-site sewer and residential community wells. Out of the 240,000 people serviced by the AWWU, approximately 10% are served by AWWU groundwater wells; this includes the entire community of Girdwood, Alaska, and the supplemental supply that AWWU provides in Anchorage.

After the 2018 Anchorage earthquake, a range of impacts were informally observed across the communities that experienced higher-intensity ground shaking. These impacts ranged from minor increases in sediment to complete loss of production due to the collapse of side walls in wells that were constructed without casing in rock zones. The informal observations were made by key professionals who are part of the Alaska water-well community. These professionals included laboratory scientists, hydrologists from both the Alaska Department of Environmental Conservation and the Alaska Department of Natural Resources, engineers from the MOA that address on-site facilities for private properties, well operators for the AWWU, engineers that work with public water systems in Alaska's rural communities, and water-well contractors that maintain and install wells around the state of Alaska. The observed impacts were communicated for inclusion in this summary through personal communication and the February 2019 Alaska Water Well Association Conference in Anchorage, Alaska.

The most prevalent impacts to groundwater and wells observed after the earthquake were increased sediment in water and disconnection of the associated piping and wiring that connects the downhole pumping equipment to the home or business. Much of the sediment cleared within hours or days. Mat-Su Test Labs, located near the area with greatest structural impacts in Palmer, Alaska, reported an increased amount of water-quality testing for bacteria by private property owners. It is unclear what motivated the property owners to test their water; however, public health warnings were issued by state officials to be aware of potential contamination with recommendations to boil water before consumption. Many wells are located near septic systems that are a part of the on-site facilities for a property, and many properties can be in close proximity to one another.

Water-well contractors indicated that they referred residents to the testing laboratories if they had water-quality concerns and responded to reports of decreased or absent production. The majority of decreased or absent production was addressed by repairing breaks or disconnections of associated piping and wiring. Worth noting were numerous failures of pitless adapters in the MOA, which is where a drop pipe that connects to the downhole pump is connected to the water line that runs to the house. This adapter is historically rigid and usually located in the side wall of the well casing below the ground surface and the depth of frost. A flexible version of the pitless adaptor is available and is slowly being incorporated by water-well contractors. The pitless adaptors that were observed to fail as a result of the 2018 Anchorage Earthquake were the ridged models.

The impact to groundwater levels was considered; however, significant fluctuations that would impact production were not observed on the basis of the available information. AWWU maintains 17 monitored wells (AWWU, 2016)¹⁰ throughout the MOA, from Eklutna to Girdwood, and reported no groundwater fluctuations that were attributed to the event. A USGS well located near Eagle River south of Highland Road was reported to decrease by 6 cm (West et al., 2020¹¹), but, again, a

significant fluctuation as it relates to potential groundwater production was not observed. Observations collected by additional water-well professionals did not include significant groundwater-level fluctuations, with the exception of an anecdotal account of artesian conditions that developed after the 2018 Anchorage Earthquake in a well located near Hiland Road near the community of Eagle River, Alaska.

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4 STRUCTURAL PERFORMANCE OF BUILDINGS

4.1 Overview

Although the magnitude of the November 30, 2018, Anchorage earthquake was relatively high, with a short epicentral distance to centers of population like Anchorage, Eagle River, and Matanuska-Susitna (Mat-Su), the observed structural damage and absence of fatalities or collapses were less than anticipated from such a large event. The depth of the event (29 miles) may have dissipated much of its energy along its long hypocentral distance, resulting in a relatively smaller shaking intensity. For instance, contrasting this event with the major damage, fatalities, and injuries of the 2011 M6.2 Christchurch earthquake of a similar epicentral distance and a 3-mile depth helps understand this effect. This can be confirmed by comparing the design-based earthquake (DBE) spectra to the recorded spectra at different building sites that experienced minor damage. In addition, the short ground-motion duration and the stricter building code requirements following the 1964 Alaska earthquake might have contributed to better building performance. However, it should be emphasized that, contrary to the public perception following the November 30 earthquake, that “buildings did well because Alaska has strict codes,” the large depth of the earthquake is believed to be the main factor to minimize damage, which is evident by the absence of fatalities, or full collapses even in the heavier damaged non-code conforming Eagle River, which is slightly closer to the epicenter.

4.2 Characteristics of Building Stock in Southcentral Alaska

Alaska is a relatively young state with a population of about 750,000, and most of the residential and commercial construction development in Southcentral Alaska took place in the second half of the twentieth century, especially after the 1964 M9.2 earthquake.

Anchorage is the largest city and borough in Alaska with a population of about 292,000. Anchorage Borough includes the city of Anchorage and the Northern Communities (Eagle River, Chugiak, Birchwood, Peters Creek, Thunderbird Falls, and Eklutna), along with Girdwood to the south of Anchorage. The population of the Northern Communities is estimated to be over 30,000. The November 2018 earthquake affected the entire Anchorage Metropolitan Area (population of 400,000), which includes Anchorage Borough and Mat-Su Borough (population of 107,000), the second largest borough in Alaska. The region that suffered the most damage from the earthquake was Anchorage's Northern Communities, especially Eagle River. Figure 4.1 shows the number of buildings in Anchorage and its Northern Communities over different decades starting in 1910. About 93% of buildings were constructed after 1950, and 88.4% of buildings were constructed after the M9.2 1964 earthquake. Figure 4.2 shows Alaska's population from 1946 to 2018.

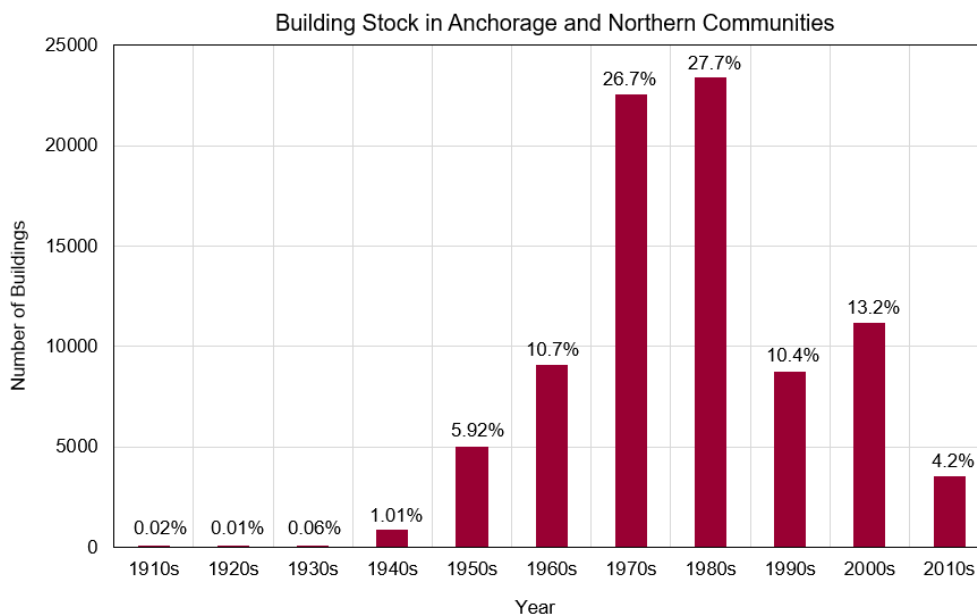
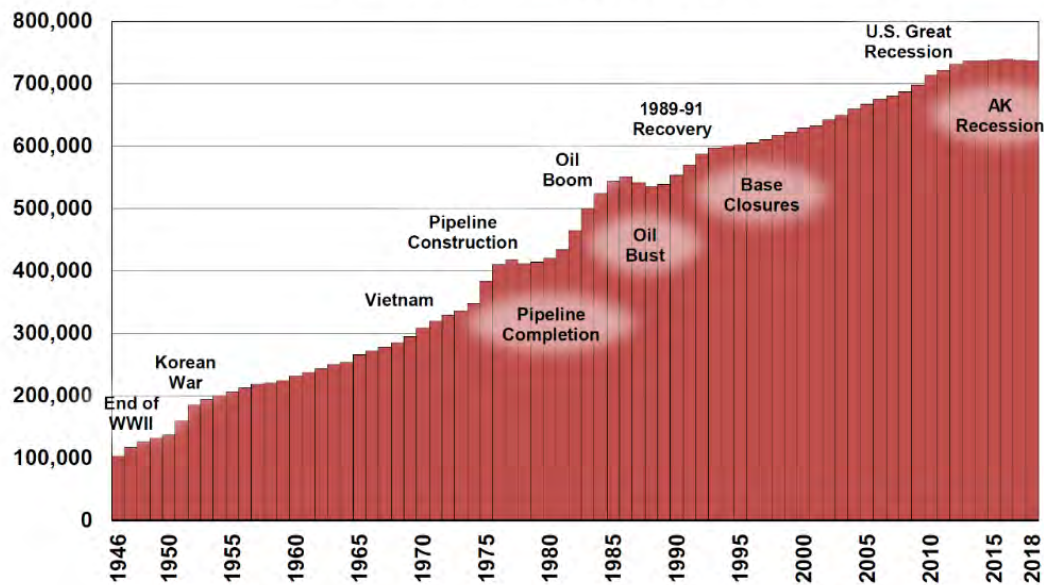


Figure 4.1. Building stock percentages by construction era in Anchorage and the Northern Communities (source: data from MOA assessor and SimCenter).

Alaska Population, 1946 to 2018



Source: Alaska Department of Labor and Workforce Development, Research and Analysis Section

Figure 4.2. Alaska population 1946–2018 (source: Alaska Department of Labor and Workforce Development, Research and Analysis Section).

The municipality of Anchorage regulates building permits only within the Anchorage Building Safety Service Area (ABSSA), nicknamed the “safe zone,” which is the “area formerly known as the city of Anchorage, the area of the Greater Anchorage Area Borough formerly known as Service Area 30, the Glenn Heights Area and the Evenson Service Area.”¹ Building code enforcement and construction inspection in ABSSA started between the late 1980s and the early 1990s.

Northern Communities/Eagle River construction began in the 1960s as a small unincorporated settler village and expanded to today’s size and population of 30,000, which includes residential, retail, commercial, and multistory construction, along with educational facilities and health clinics. The Northern Communities are outside ABSSA, so building codes are not enforced and building inspection is not required.

Anchorage building stock dates back to the 1910s, when building the railroad motivated urbanization of the region for workers and settlers. However, the size of building stock from 1910 to 1950 is rather limited today (Fig. 4.2). Significant construction development took place in Anchorage starting in the 1950s. However, following the 1964 M9.2 earthquake, significant changes in building codes tightened construction quality to be seismically resistant in important buildings, as will be discussed subsequently. According to the municipality of Anchorage (MOA), the estimated number of buildings in the Anchorage Bowl alone is 80,000–90,000. According to Anchorage Borough’s assessor, the number is about 84,500 buildings in the Anchorage Bowl and in Eagle River. The majority of building stock in Anchorage today (88%) is of post-1964 construction, with significant additions in many city neighborhoods, especially in the South, after 1990. However, a significant percentage of this building stock predates the municipal code enforcement and seismic details required in the early 1990s. In particular, about 72% of Anchorage and the Northern Communities’ building stock predates 1990, which implies high uncertainty about their severe seismic damage or collapse risk under the maximum considered earthquake (MCE). This percentage might constitute an indicator of the existing building problem in the area.

Mat-Su’s early construction dates back to 1917. There are about 30 historic buildings in Mat-Su that were built between 1917 and 1950. The majority of buildings in Wasilla (population of 10,500) and Palmer (population of 8,000), the largest cities in Mat-Su Borough, are of post-1970s construction. In summary, the majority of the building stock in the Anchorage

and Mat-Su Boroughs is less than 35–40 years old. However, this does not necessarily imply that this young building stock is seismically-resistant as will be explained in the following section.

Wood construction is the primary system for residential buildings in both the Anchorage and Mat-Su Boroughs. In the 1950s, mixed-use, office, public, and multistory buildings shifted toward concrete construction. After the 1964 M9.2 earthquake, steel construction of these building types prevailed due to widespread damage of non-ductile concrete buildings then. Besides seismic design advantages, steel construction was especially appealing because of the short construction season in Alaska (May to September). However, with the development of ductile concrete details in the 1980s, concrete construction gained ground in many buildings in Anchorage, especially mid-rise buildings, parking structures, and many office buildings. Concrete-masonry-unit (CMU) wall construction has been very popular in schools, retail buildings, and many low-rise buildings since 1964, in part due to lower construction cost as the CMU blocks are produced locally from imported cement, unlike other building materials that are imported entirely from other states. Many of the relatively new buildings in the Anchorage and Mat-Su Boroughs, after the 1980s, used CMU construction.

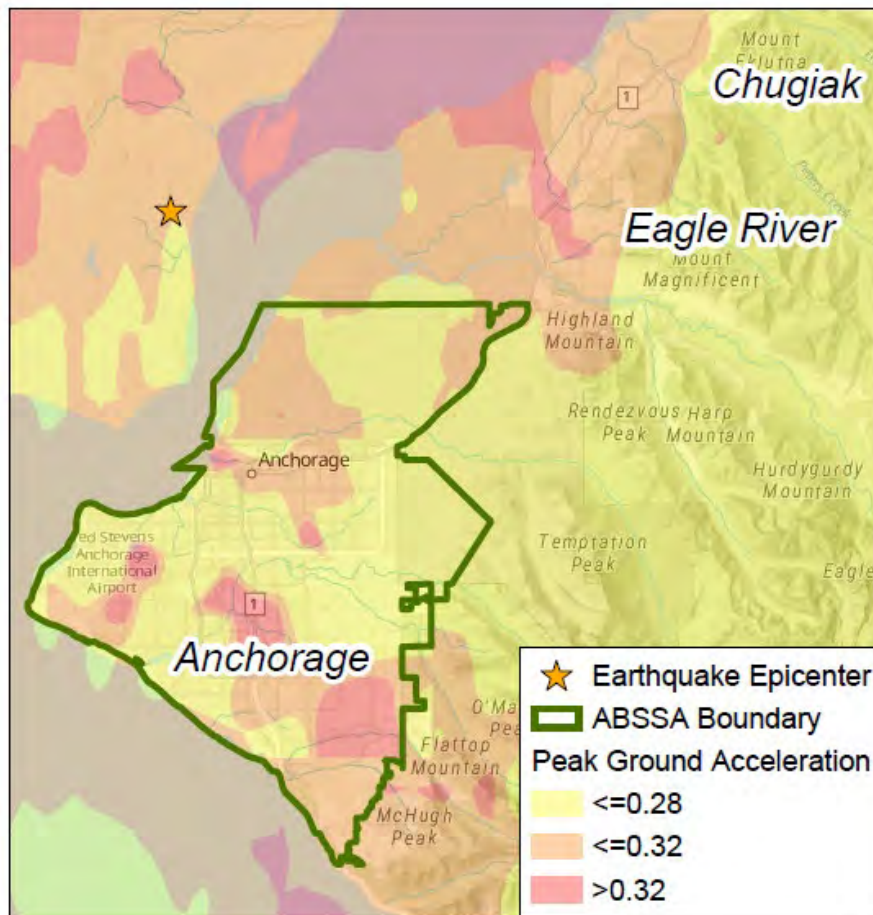
A special problem with many public and multistory buildings in Anchorage is building additions/extensions. Many buildings, including schools and major hospitals, were built over decades using different building codes, not necessarily requiring full upgrades to the latest code of the original building being expanded as per Anchorage Existing Building Code. This resulted in some structural irregularities and seismic-resistance inconsistencies.

4.3 Building Codes, Practices, and Code Enforcement

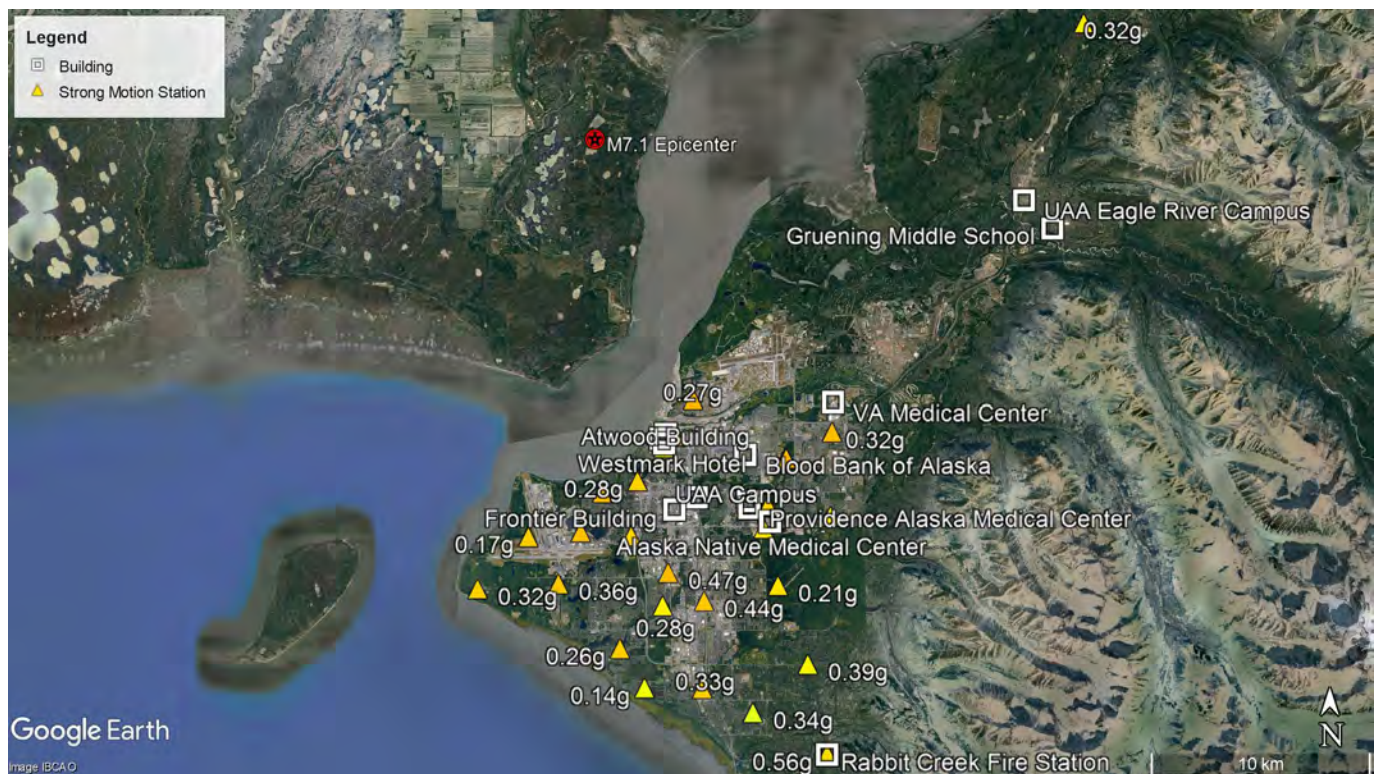
Following the 1964 M9.2 Alaska earthquake, seismic building regulations significantly improved and tightened in Alaska. However, seismic details were not introduced in the area until the mid-1980s, following the 1979 *Uniform Building Code* model. The 1964 earthquake led to major seismic policy changes in Alaska and nationwide that led to stricter state building codes and later led to the creation of the National Earthquake Hazards Reduction Program in 1977. Alaska is currently credited to be one of the strictest states in seismic safety code requirements because of the local Alaska code amendments to the *International Building Code (IBC)* and the *International Existing Building Code (IEBC)*, which the state adopts following every code cycle of the *IBC* and *IEBC*. Until October 2020, the 2012 *IBC* and *IEBC*, with their Alaska local amendments, were adopted as the latest building codes, lagging behind the most recent 2018 *IBC* and *IEBC* by two cycles for logistical reasons. The new 2018 *IBC* and *IEBC* have been adopted starting 27th of October, 2020

The level of code enforcement and building inspection varies widely across the state. For instance, building codes are not enforced and construction is not inspected in the Northern Communities in Anchorage Borough, although they fall under the jurisdiction of the MOA for most services. This is because the local councils of the cities and towns in the Northern Communities voted not to be part of the MOA for building construction purposes. This situation applies to both residential and nonresidential buildings. Similarly in the Mat-Su Borough, code conformance is optional, but several local contractors choose to voluntarily follow MOA requirements.

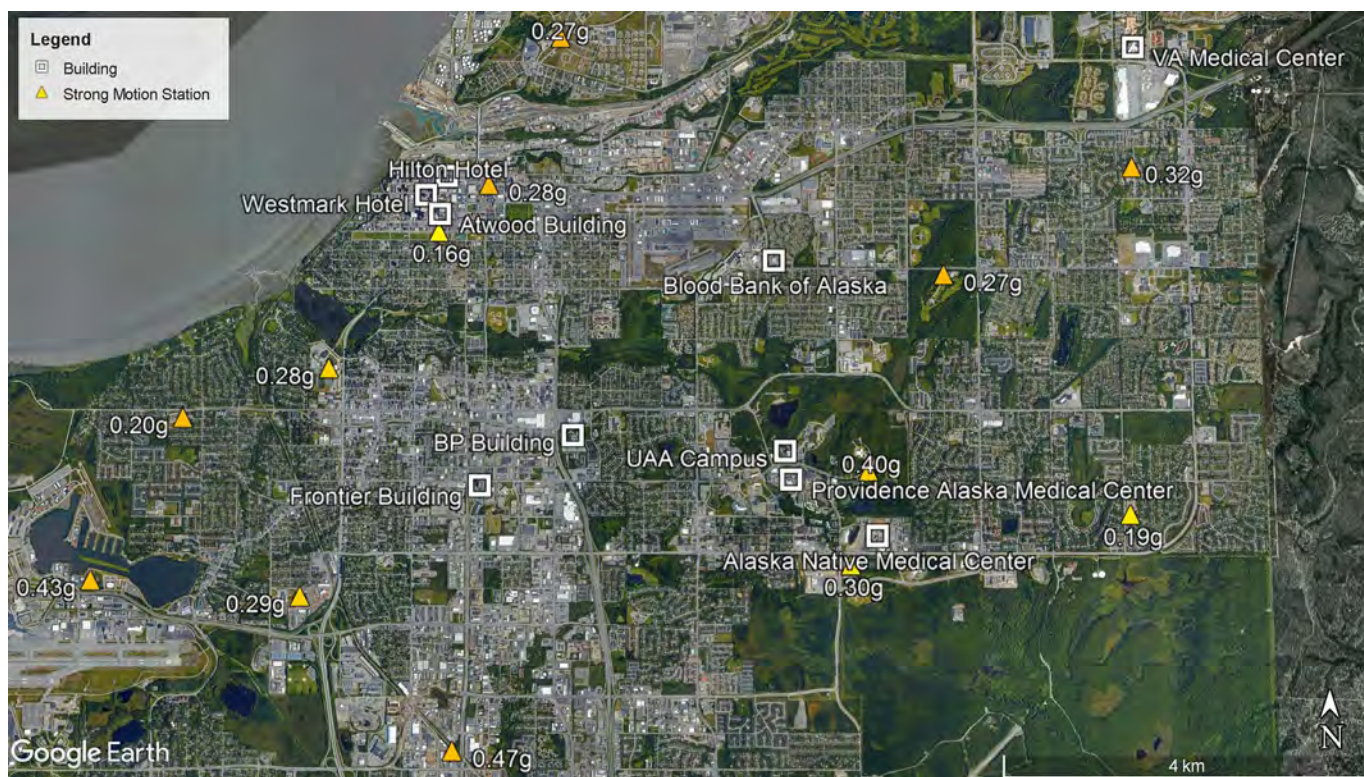
According to the MOA, building codes and construction inspection are currently strictly enforced in the “safe zone,” which represents the city of Anchorage and Anchorage Bowl (ABSSA, Figure 4.3) but not Northern Communities. The years of 1981–1982 mark the construction boom in Anchorage and the Northern Communities due to increased Trans-Alaska Pipeline System oil production, which started in 1977. The oil prices peaked in 1981, leading to 5 years of substantial construction, with average and low quality in many cases. The demand for building permits during that time was substantial enough that the MOA was not able to keep up with demand, so inspections and code enforcement were loose, even in the Anchorage Bowl, according to personal communications with many MOA and Anchorage engineering professionals (David Sheer, Ross Noffsinger, et al., pers. comm., 2019). The full strict enforcement of codes in the Anchorage Bowl started around the early 1990s. Thus, it is safe to assume that any building constructed after 1994 within the city limits of Anchorage is seismically designed and detailed according to their respective construction year code. The Federal Emergency Management Agency found, on the basis of information from after the November 2018 earthquake, that the requests for financial assistance to repair damages in residential buildings in Eagle River were five times those in Anchorage for houses built after 1994.² Prior to the mid-1980s, there is no information on the size of building stock that is properly designed and detailed seismically; thus a safe assumption is that any building in Anchorage predating the mid-1980s is not engineered, code conforming or seismically detailed, unless otherwise proven through construction documents and inspection records or as certified by a professional structural engineer.



(a)



(b)



(c)

Figure 4.3. (a) November 2018 Anchorage earthquake intensity map showing ABSSA boundary (source: Thornley et al., 2019).² (b) PGA map of Anchorage and Northern Communities showing the locations of some of the structures investigated in this report; and (c) A close up of a PGA map of Anchorage showing more detailed locations of some investigated buildings.

Such variations in code conformance help explain the heavier damage observed in Eagle River and the Northern Communities in contrast to Anchorage, as will be presented next.

During field reconnaissance by the EERI team, we observed much heavier damage in Eagle River compared to Anchorage for the same types of buildings (residential, commercial, and office buildings), as can be seen in subsequent sections. Furthermore, the MOA earthquake damage inspection records following the event show interesting observations. By January 30, 2019, the MOA had inspected 1,298 buildings in Anchorage, giving 28 red tags (0.025% of building stock) and 606 yellow tags. By the same date, the MOA had inspected 851 buildings in the Northern Communities, giving 62 red tags (0.43% of building stock) and 252 yellow tags (Figure 4.6). These numbers should be compared with respect to the size of building stock in each region, which reveals that the number of red tags given in the Northern Communities was 20 times the number in Anchorage, while the number of yellow tags given in the Northern Communities was 3 times the number in Anchorage. A similar comparison of the MOA inspection records as of September 2019 reveals that the numbers of red tags and yellow tags given with respect to building stock size in the Northern Communities were 18 times and 2 times the numbers given in Anchorage, respectively. Askov et al.²² estimated the red tag ratio in Northern Communities compared to Anchorage is about 17. A test-bed exploratory study was performed by the Natural Hazards Engineering Research Infrastructure (NHERI) SimCenter in 2019³ (Figure 4.4) under the M7.1 November 30 Anchorage earthquake projected 14.5% loss of building stock (red tags) in Anchorage and the Northern Communities (approximately 3,800 buildings). It is worth mentioning that the SimCenter study was a preliminary study based on rough estimates of building characteristics.

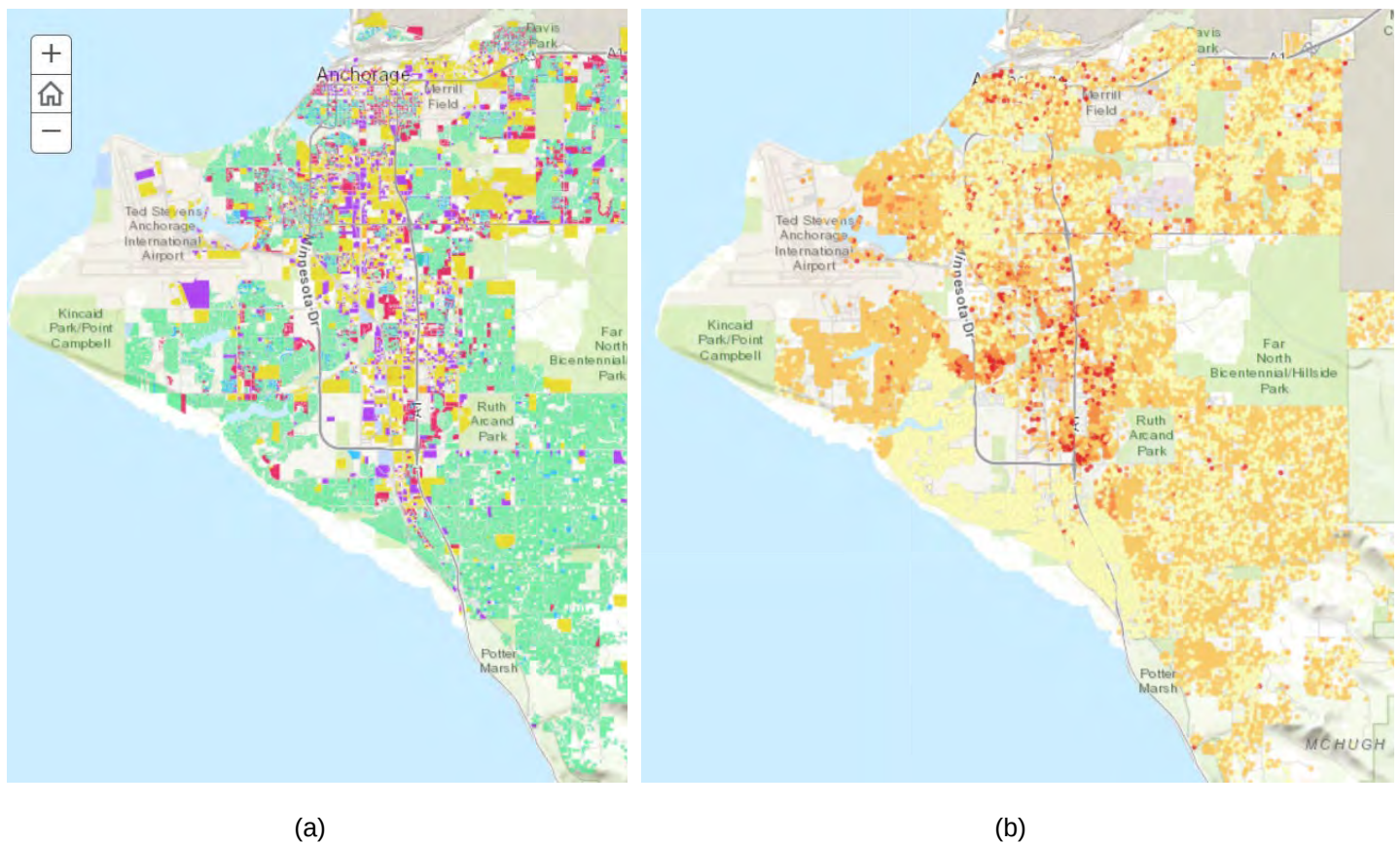


Figure 4.4. (a) Building stock classification for the Anchorage Bowl and SimCenter exploratory simulation³ under the M7.1 November 2018 earthquake. (b) Projected red-, yellow-, and orange-tagged buildings based on SimCenter simulation³ under the M7.1 November 2018 earthquake, using the loss ratio.

Buildings in Southcentral Alaska, particularly Anchorage Metro buildings, mostly fall into Seismic Design Category D, with *American Society of Civil Engineers (ASCE) 7-IBC* spectral acceleration of $0.6g$ for a 1-second period (S_1) and $1.5g$ for a 0.2-second short period (S_s). Sample design spectra are plotted in Figures 2.10, 2.11 and 4.5.

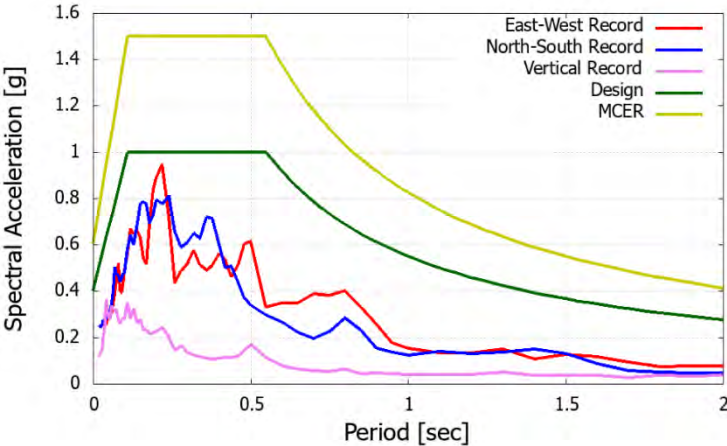
4.4 Damage Correlation to Ground Shaking

The maximum recorded peak ground acceleration (PGA) for the event was $0.56g$ in South Anchorage. The prevailing shaking intensity was less than $0.20g$ – $0.32g$ across the affected region, with the exception of isolated spots in Anchorage, which received more than $0.32g$, as shown in Figure 4.3. This prevailing shaking intensity roughly corresponds to 50%–60% of design PGA. This observation can be further confirmed by comparing the DBE spectra to the recorded ground-motion spectra at several sites and buildings, as shown in Figures 2.11, 2.12, and 4.5. The damage correlated well with shaking intensity in most regions. However, exceptions exist, such as the limited damage in South Anchorage, where the highest PGA was recorded, although non-structural damage was evident in some cases. This can be attributed to several factors, including the nature of buildings in that city extension region, which are mostly new upscale one-story or two-story timber residential or retail buildings on stiff soil or rock. The heaviest observed damage in Anchorage in Sand Lake, which was mostly geotechnically related, correlated well with the recorded PGA, as can be seen from the number of red- and yellow-tagged buildings (Figure 4.6). The damage at the University of Alaska campus was mostly nonstructural, correlating well with the shaking intensity of $0.21g$ recorded on campus. Observed damage in the Northern Communities, especially Eagle River (12 miles north of Anchorage), was more extensive than in Anchorage. Lack of building code enforcement in the Northern Communities is the primary contributing factor to their heavier damage. Due to the lack of seismic sensors in the Eagle River area, only one station that recorded $0.3g$ PGA north of Eagle River, there is little evidence other than “Did You Feel It?” (DYFI) reports to suggest that its shaking intensity was relatively higher. It is instructive to compare the building inspection tagging maps in Figures 4.6 and 4.7 to the ground-shaking intensity maps (Figures 4.3, 4.7, and 4.8) to correlate the ground motion with the level of damage. The Mat-Su Borough has scarce seismic stations. NSMP Station AHOU in Houston City Hall recorded $0.23g$ PGA, while Palmer K218 station recorded

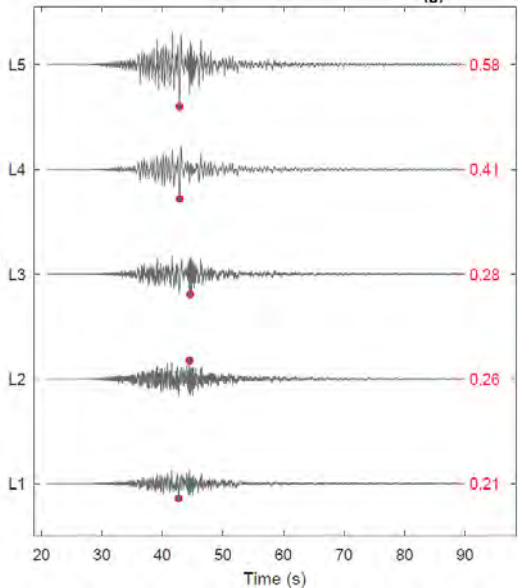
0.138g maximum PGA. NSMP Station AMJG in Wasilla recorded 0.688g maximum PGA. It is not possible, however, to build a PGA map in Mat-Su, since it only has these three stations, unless correlation with DYFI and damage reports is performed. Thus, it is possible to speculatively correlate Mat-Su damage (Figures 4.9, 4.10, 4.11, and 4.12) with DYFI intensity maps. It seems, from observing the recorded spectra at several stations and correlating that with the level of nonstructural damage, that the short-period structures were more affected by shaking than long-period structures in most regions, which is line with other observers findings.⁴ It also appears that the north-south component of the ground motion was more significant than the east-west component for the period range above 0.5 second, evidenced by damage pattern observed at several locations in Anchorage and by the recorded spectra (Figure 4.5). As will be presented in this chapter, the taller buildings in downtown and midtown Anchorage experienced minor nonstructural damage. However, one should also factor in the relatively small number of taller buildings, their relatively young age, and the special care given to their design and construction.



(a)



(b)



(c)

Figure 4.5. (a) Engineering and Industry Building (EIB), University of Alaska, Anchorage (UAA) (photo: Wael Hassan) and its (b) response spectra and (c) recorded floor acceleration (source: Utpal Dutta, University of Alaska, Anchorage, pers. comm., 2019).

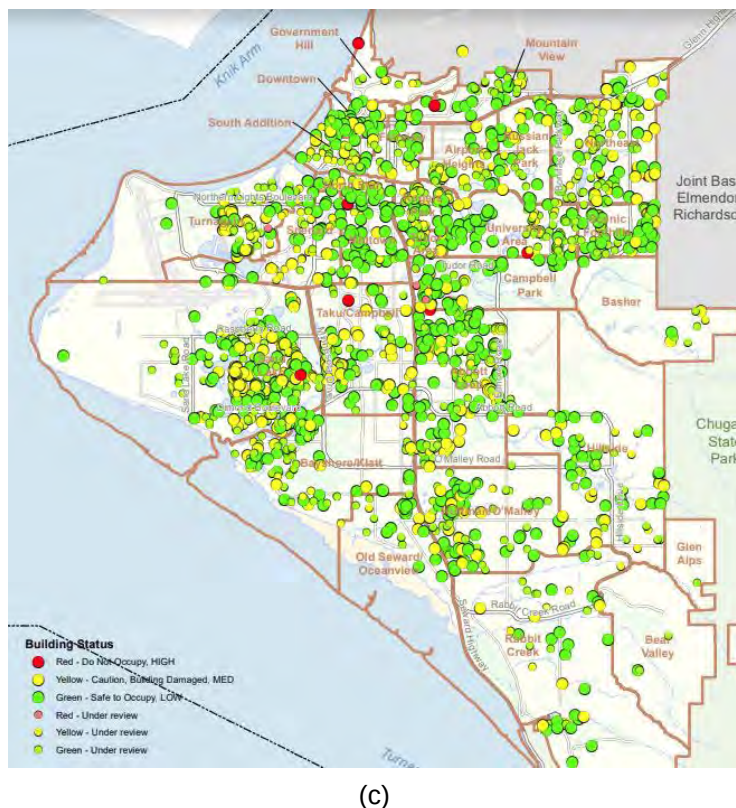
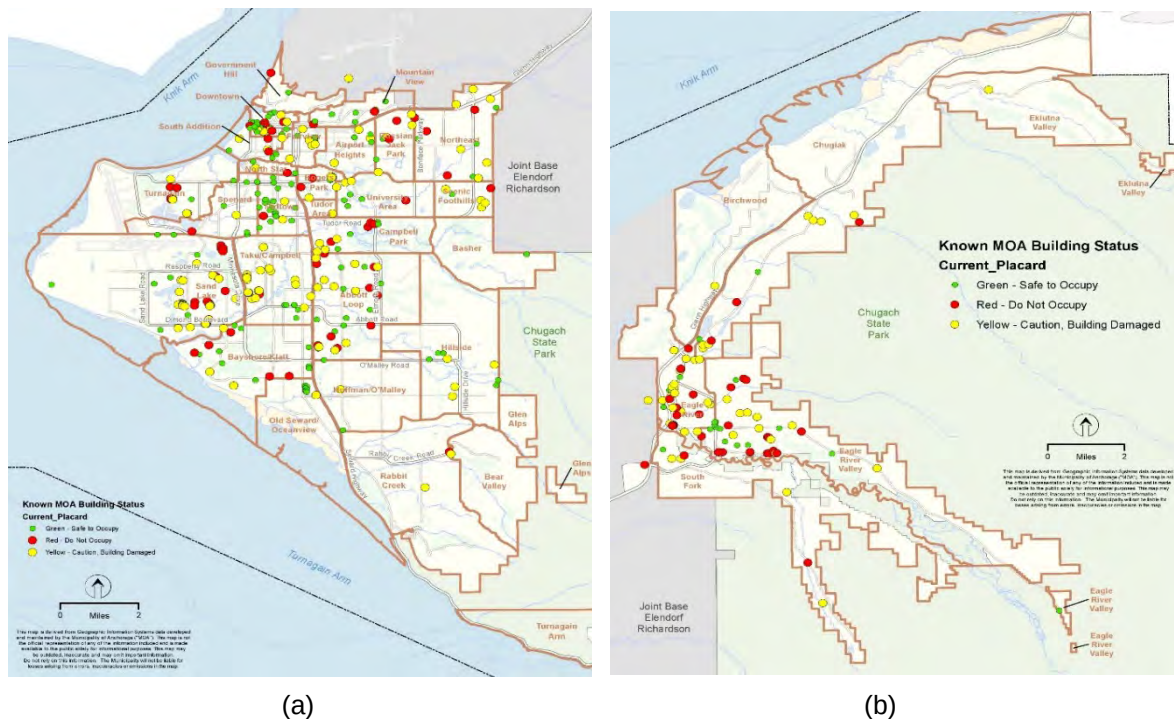
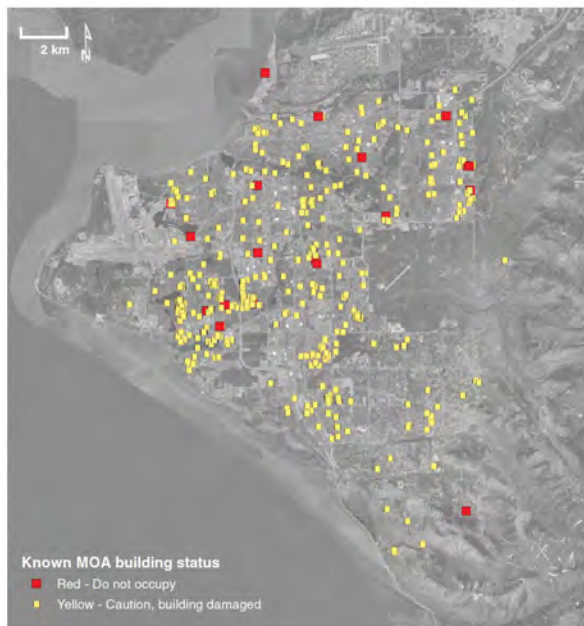
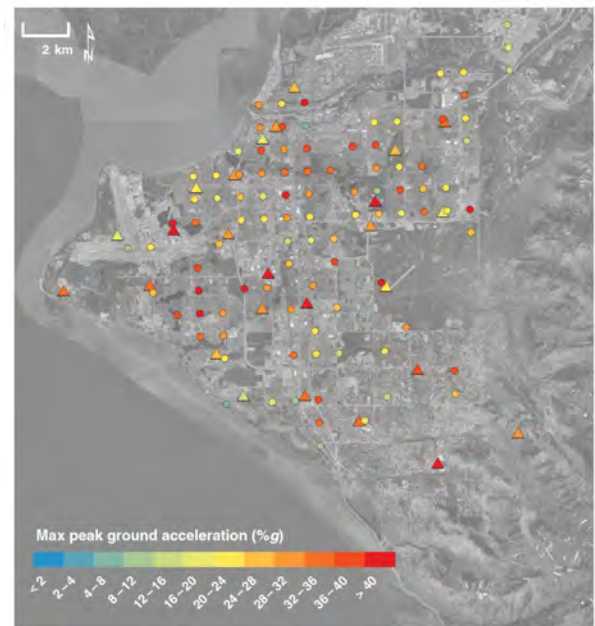


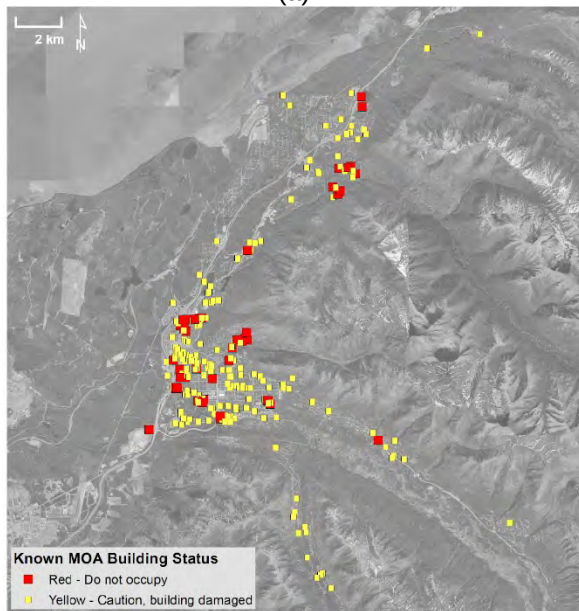
Figure 4.6. MOA inspection and building tagging distribution: (a) Anchorage and (b) Northern Communities, December 10, 2018; (c) Anchorage, January 30, 2019 (source: MOA).



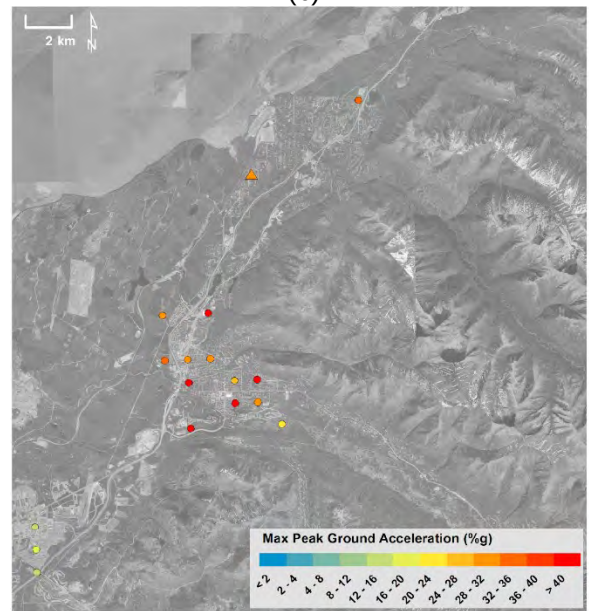
(a)



(b)



(c)



(d)

Figure 4.7. Damage correlation to ground shaking: (a, b) Anchorage Bowl and (c, d) Northern Communities; (a, c) MOA placard colors and (b, d) recorded PGA (triangles) supplemented with the estimated PGA (circles) from DYFI reports (source: West et al., 2019⁵).

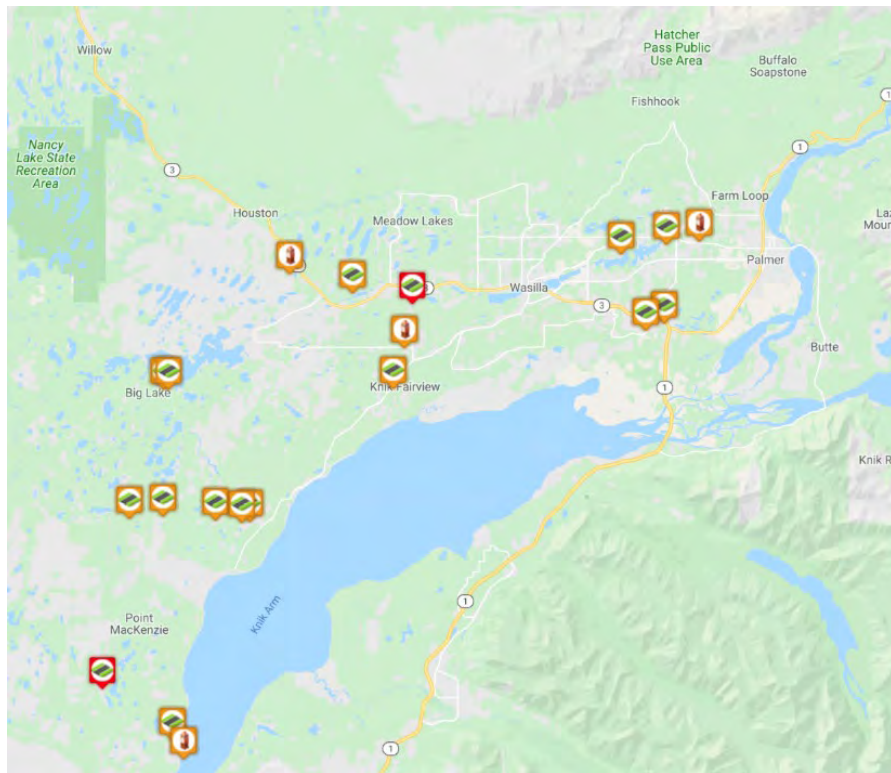


Figure 4.10. Mat-Su Borough: residential buildings with major structural damage/collapse (source: Mat-Su Borough Records).

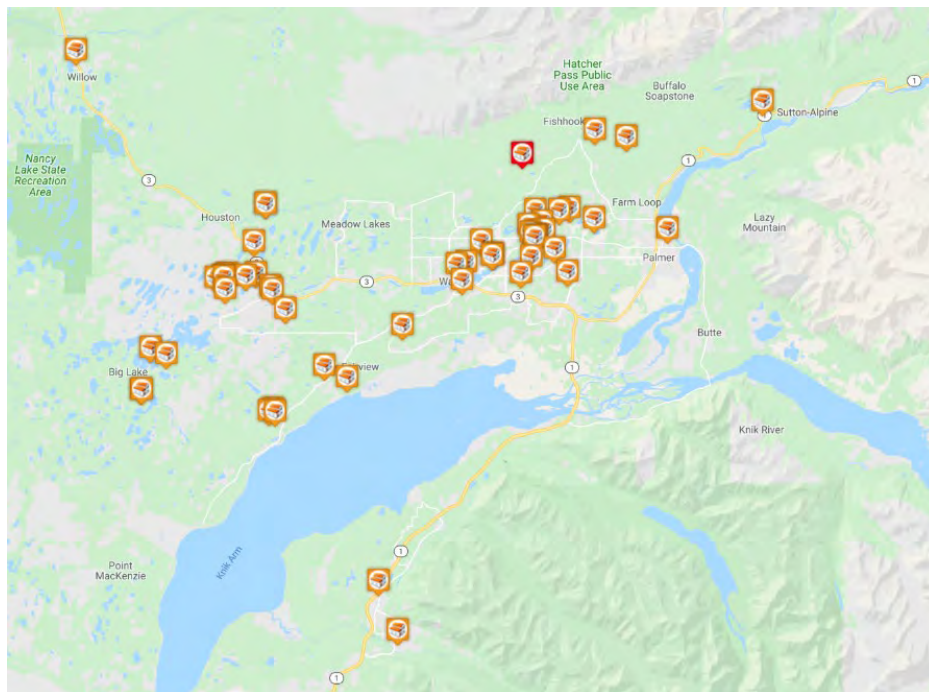


Figure 4.11. Mat-Su Borough: public buildings and infrastructures with major structural damage/collapse (source: Mat-Su Borough Records).

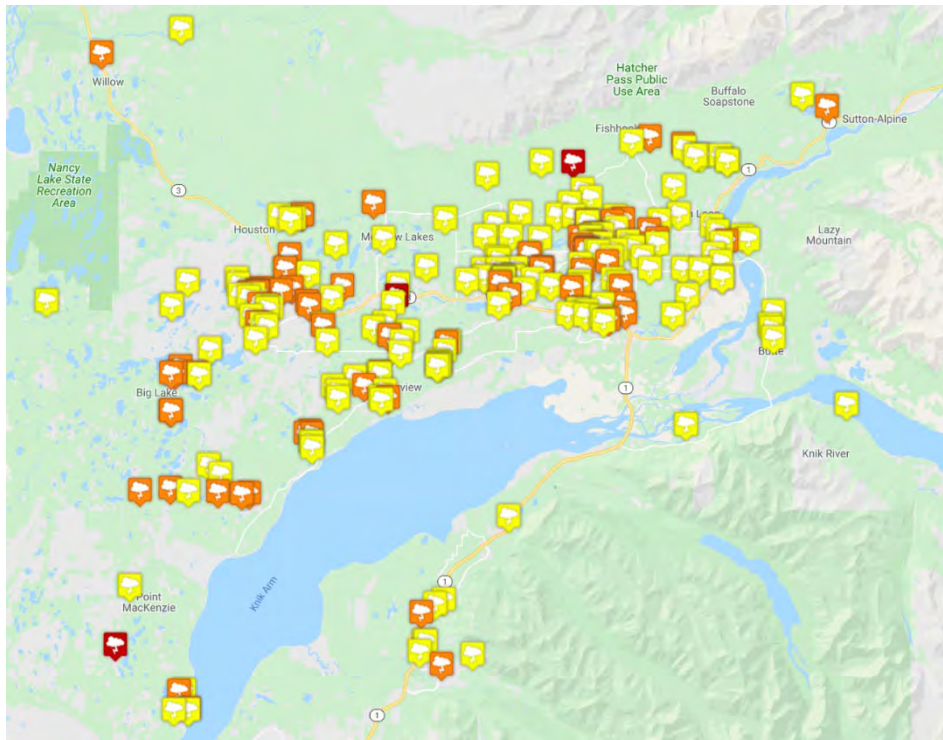


Figure 4.12. Mat-Su Borough: Muni tagging for residential buildings, public buildings and infrastructures, and private businesses; red tag: destroyed, orange tag: major damage, yellow tag: minor damage (source: Mat-Su Borough Records).

4.5 Observed Damage in Reinforced Concrete Buildings

Reinforced concrete frame and shear wall buildings experienced light structural damage in both the Anchorage and Mat-Su Boroughs. Some exceptions are isolated cases, Fig. 4.15 for example, in which critical concrete elements experienced structural damage that posed partial or full collapse risk, especially with many aftershocks higher than M_w 5. However, no partial or full collapse was reported in any concrete building as a result of the November 30 earthquake or the following aftershocks. This discussion excludes CMU-wall buildings, which are presented in the next section.

The most common observed structural damage was shear cracking in structural walls, flexural and shear cracking in some girders, flexural and splitting cracking in columns, slab-on-grade cracking, and flexural cracking in topping slabs in composite construction. In particular, diagonal and cross shear cracks in concrete shear walls, especially in older construction, were observed in several buildings, including schools, hospitals, and office buildings. In some of these buildings, structural review found these walls to be under-designed. Figures 4.13 and 4.14 show concrete shear wall extensive shear cracking in a hospital and a school buildings in Anchorage and Mat-Su, respectively. Vertical cracks and diagonal cracks in concrete walls around openings were also observed. The hospital building shear wall cracks in Figure 4.14 were concentrated in the core wall over the first two stories on both faces of each individual wall of the building core wall.



Figure 4.13. Concrete core wall with cross shear cracks in a multistory Anchorage building (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)

Figure 4.14. (a) Concrete shear wall with diagonal cracks (photo: Chris Motter), (b) shear wall diagonal crack at a parking structure (photo: Wael Hassan), (c) concrete-parapet cracking (photo: Wael Hassan), (d) concrete composite slab with flexural cracking (photo: Janise Rodgers), and (e) cast-in-place slab with flexural cracks (photo: Colin Maynard⁸).

Concrete girder shear and flexural cracks appeared on a few occasions. The case of the Westmark Hotel in Anchorage is of particular interest. The building is a 14-story CMU and concrete-frame hotel building built in 1970 (Figure 4.15). Minor hairline shear cracks, 1/32 of an inch wide, appeared in three transfer concrete girders in the first floor supporting the 14 floors above because of the November 30 earthquake, and the building was yellow-tagged (Figure 4.15). The large number of strong aftershocks has exacerbated the structural damage in many buildings, including the Westmark Hotel, in

which these concrete girder shear cracks kept widening to about 5/32 of an inch, warranting immediate retrofitting. Concrete jackets were provided to girders, supporting columns, and foundations. The hotel was closed to undergo structural retrofitting for 5 months following the earthquake.



(a)



(b)



(c)



(d)

Figure 4.15. (a) Westmark Hotel (photo: Wael Hassan), (b) transfer-girder shear cracking repair (photo: Wael Hassan), (c) transfer-girder initial state (photo: PDC Engineers), and (d) aftershock shear crack (photo: PDC Engineers).

Vertical-column splitting cracks in moment-resisting concrete frames were observed in a few cases. The Frontier Building in Anchorage is worth mentioning. The 14-story 1981 moment-resisting-frame concrete building experienced hairline to minor overstressing concrete cover splitting cracks in many of the circular exterior and corner columns at stories three, four, and five (Figure 4.16). The crack length ranged from 3 inches to 20 inches, while the crack width was about 1/32 to 1/16 of an inch. The estimated fundamental period of the building (Çelebi, 2020⁹) is 2.2 seconds. The building experienced a relatively low PGA of 0.193g; however, the shaking was strong, perhaps because of its relatively higher stiffness as a concrete-frame building. A few other examples for concrete column–overloading splitting and flexural cracks are depicted in Figure 4.17.



Figure 4.16. Typical splitting crack in exterior-column cover. Most exterior and corner columns on levels one through three exhibited such cracks with variable sizes (photo: Wael Hassan).



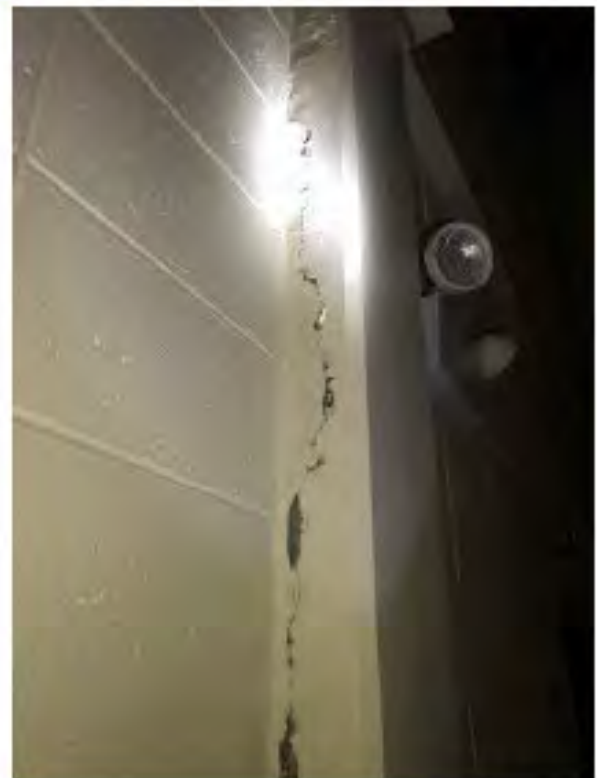
(a)



(b)



(c)



(d)

Figure 4.17. Concrete-column damage: (a) flexural cracks (photo: Patrick Murray) and (b–d) splitting cracks (photos: Joint Base Elmendorf-Richardson (JBER)).¹⁰

Fiber-reinforced polymer (FRP)-retrofitted concrete buildings performed satisfactorily during the earthquake, with only minor flexural cracks in unstrengthened columns and minor cracking in shear walls, with no sign of FRP debonding

throughout. An example of such building performance is Parking Structure 1 at Providence Alaska Medical Center (PAMC; Figure 4.18) and McKinley Tower. The PAMC parking structure did not exhibit any FRP-retrofitted column damage, but exhibited some minor cracking in non-strengthened columns, (Figs. 4.18 and 4.19b,c). It is worth noting that the FRP retrofitting project featured also separating the short parapets from columns to avoid captive column condition, which was successful in preventing damage to columns (Engineering Manager, Providence Alaska Medical Center, pers. comm., 2019). Inspecting the McKinley Tower, a high-rise apartment moment-frame concrete building constructed in 1951 and considered the first tall building in Anchorage, revealed only negligible cracks.¹¹ It is worth mentioning that this building was heavily damaged in the 1964 M9.2 earthquake and was upgraded in 1998 to conform to the then-current seismic codes, but the retrofit project was abandoned due to high cost. The building was retrofitted via FRP retrofitting system again in 2005, which did not show visible signs of damage or deterioration after the November 2018 earthquake. Little evidence exists, based on pull-out field tests, to support FRP debonding in some external columns of Anchorage International Airport, however, the subject is still under investigation at the time of report writing (pers. comm. 2019).



(a)



(b)



(c)



(d)

Figure 4.18. (a) PAMC Parking Structure 1 with building retrofitting via (b) FRP wrapping. (c) No signs of debonding were observed following the earthquake. The retrofitting project included (d) separating the concrete parapet from the column with elastic material to avoid a short-captive-column condition (photos: Wael Hassan).

Minor cracking was observed in precast concrete buildings, especially as splitting and minor crushing at connections (Figure 4.19e,f). Concrete stairwell separation and splitting cracks and corner concrete crushing were observed in some cases (Figure 4.19a). In limited cases, multistory-tall concrete columns that were unsupported laterally underwent large inelastic deformations, rendering the columns unstable under large permanent residual drift.¹²



(a)



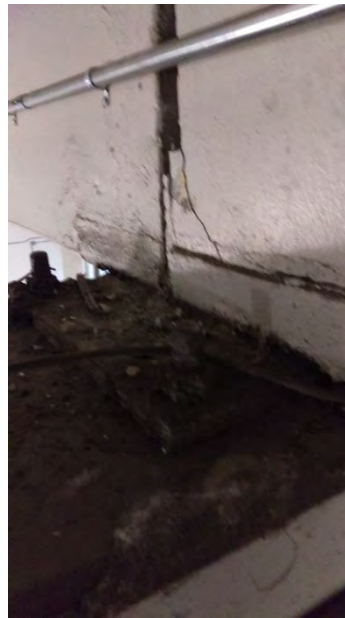
(b)



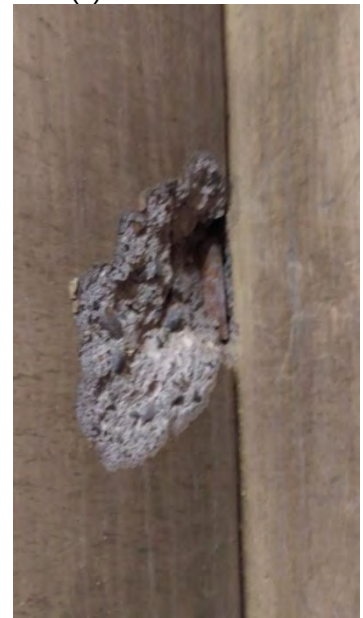
(c)



(d)



(e)



(f)

Figure 4.19. (a) Concrete stair crushing and cracking, (b) column shear flexural cracking and concrete-girder spalling, (c) column flexural cracks, (d) retaining/bearing-wall vertical cracks (photos a-d: Wael Hassan), (e) precast-girder splitting cracks, and (f) precast-wall minor crushing (photos e-f: Colin Maynard¹³).

Minor vertical and diagonal cracking in concrete retaining walls was observed in many buildings, even in new construction (Figure 4.19d). This was especially evident in retaining foundation walls supporting vertical loads from multistory frame buildings, in the case of ground slope/grades where the retaining wall extends above ground for up to one story in height. Seismic joints performed satisfactorily as per the design's intent, causing minor aesthetic damage but preventing major structural damage. In several warehouses, the roof diaphragm separated from the concrete tilt-up walls. In a swimming pool in Palmer, minor shear cracks occurred throughout the walls²³.

Concrete-foundation splitting and flexural cracking and crushing were evident in many buildings of different types, including steel, CMU, and timber buildings (Figures 4.20d and 4.41). In most cases, this foundation damage was attributed to geotechnical problems, and only a few cases were due to problems with superstructure design (Figure 4.41).



(a)



(b)

Figure 4.19. (a) concrete beam displacement at connection to wall; (b) concrete spalling due to failure at beam to wall connection, likely a precast beam. (photos: Reid Middleton, ASD)

It is worth mentioning that, on many occasions, the team inspected buildings constructed prior to the 1980s, which lacked seismic details. However, access to vulnerable structural elements such as columns and beam-column joints was not possible, as they were covered with wall finishes. In one occasion at least, the EERI Team suspected flat plate punching/diaphragm damage in an older concrete building due to extensive finishes cracking around columns, but it was not possible to be confirmed. In another occasion, the insistence of EERI Team to inspect the inside of concrete shear wall through an elevator shaft hatch revealed hidden core wall shear cracking. Thus, susceptible hidden structural damage could be present and unnoticed. Thorough structural review and inspection, including exposing vulnerable elements of non-ductile concrete buildings, after such a significant earthquake should be mandated, especially for essential and critical facilities. Such hidden damage in non-ductile concrete buildings includes concrete flat-plate punching cracks, diaphragm shear cracks, unreinforced beam-column-joint shear cracks, column shear and lap-splice-bond cracks, and cover spalling and shear wall diagonal cracks. For example, cracking in unreinforced beam-column joints in older buildings can occur as early as 0.8% interstory-drift ratio (Hassan, 2011)¹⁴ and (Hassan and Moehle, 2012),¹⁵ which may have been reached by several concrete buildings during this earthquake. It was reported by some local structural engineers that they found column structural damage when they removed the cracked architectural finishes. Cracks in gypsum ceilings can be a sign of damage from floor diaphragm failure.

4.6 Observed Damage in CMU and Masonry Wall Buildings

The damage observed in CMU-wall buildings following the November 2018 earthquake was especially remarkable. CMU construction has been a popular system since the 1960s in Alaska for many types of buildings, including schools, low-rise

office buildings, retail and commercial buildings, sports facilities, and warehouses, among many others. One reason for this is the relatively lower cost of local production of CMU blocks from imported cement versus the high cost of other building materials that are fully imported from other states. Widespread CMU wall damage occurred, ranging from minor cracking to major wall instability, reaching the onset of collapse in a few buildings.

The most common CMU damage patterns observed were connection failure between the CMU wall and floor system (Figures 4.21, 4.22b,c, and 4.23), floor joist/beam unseating off CMU walls (Figure 4.25), and CMU wall-wall connection failure (Figures 4.22a and 4.24). Many examples of such damage patterns across both the Anchorage and Mat-Su Boroughs indicate the special vulnerability of CMU connections in the region. Some of the buildings that experienced this kind of damage were built after 1985 (and even the 1990s) presuming that seismic details were in effect at the time of construction. Several root causes might have led to CMU wall-floor and wall-wall connection seismic vulnerability, including poor design and detailing deviating from codes, poor construction of the connection details (both causes were evident in multiple buildings, including schools as indicated in Chapter 6 of this report), the absence of positive steel, or the absence of seismic details altogether. Many of the CMU walls with this type of damage warranted immediate red tagging of the building because of significant instability concerns about floor collapse and out-of-plane deformation of the wall, especially with a large number of significant aftershocks. Lateral restraining supports (steel or wooden props) were installed (Figure 4.21) in most cases.



Figure 4.21.a. CMU wall-wall and wall-floor connection failure and out-of-plane deformation of a CMU wall, leading to incipient collapse (photo: Wael Hassan).



(a)



(b)



(c)

Figure 4.21.b. (a) CMU wall-wall failure, (b) wall-floor connection failure (photos: Wael Hassan), and (c) parapet damage (photo: Chris Motter).



(a)

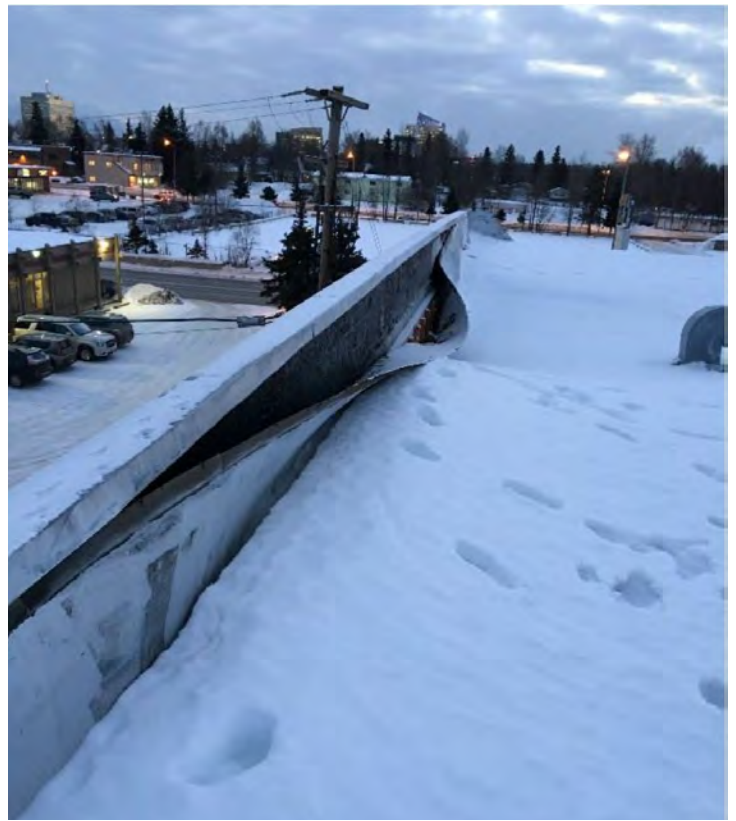


(b)

Figure 4.22. An example of CMU wall-floor connection failure with absence of seismic reinforcement. The circled portion in (a) is shown with further detail in (b) (photos: Wael Hassan).



(a)



(b)

Figure 4.23. (a) Interior CMU wall detachment from floor framing and (b) exterior CMU wall detachment from floor framing and roof partial collapse (photos: PND Engineers).



(a)



(b)



(c)

Figure 4.24. Examples of CMU wall-wall connection failures (a, b) at steel columns (photos: Wael Hassan) and (c) with no column (photo: JBER29).



(a)



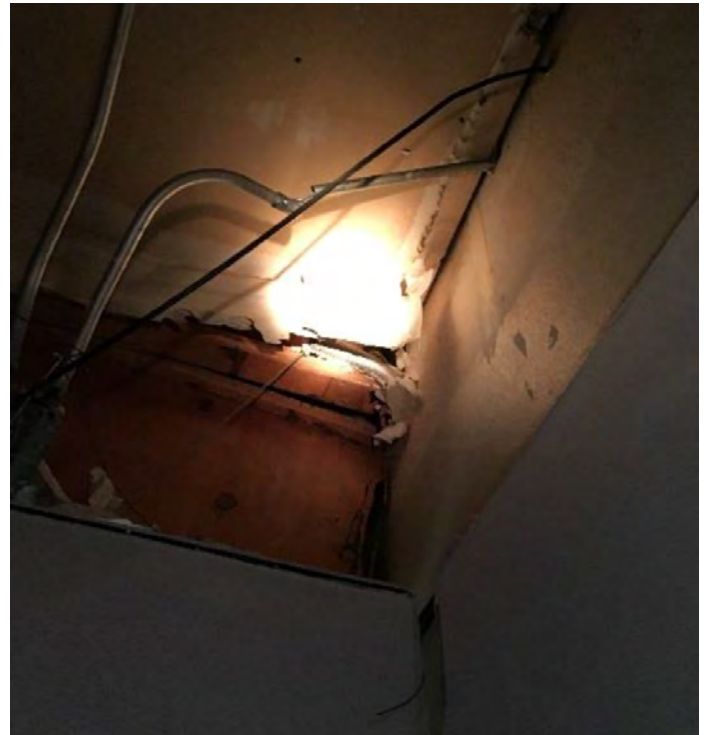
(b)



(c)



(e)



(d)

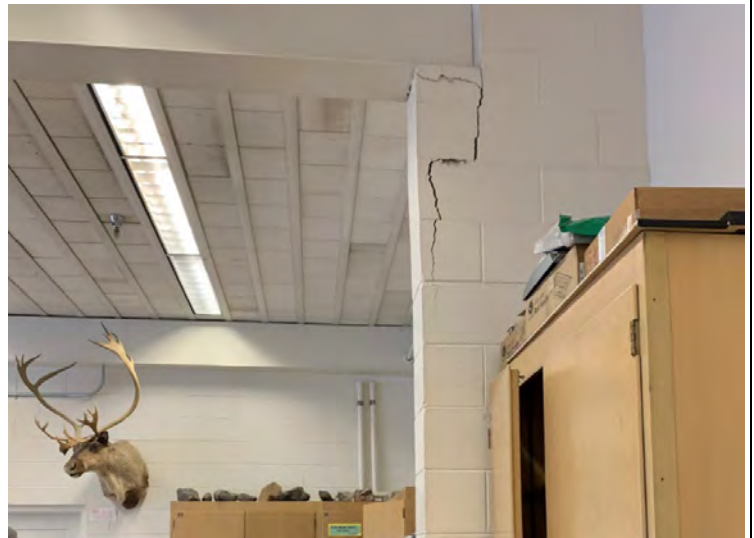
Figure 4.25. Examples of CMU wall-beam connection failures: (a) steel beam–CMU wall connection failure at Mat-Su School (photo: Bill Noyan), (b) CMU wall connection failure at an Anchorage retail building (photo: Wael Hassan), (c) steel beam–CMU wall connection damage (photo: JBER²⁹), (d) lack of seismic anchorage steel length and hook (photo: Colin Maynard⁴¹), and (e) steel joist off-seating to CMU wall (photo: PND Engineers).

To present an example of CMU wall-wall and wall-floor connection failure, severe damage was observed to a masonry pawn shop building in Eagle River (Figure 4.21). The building appeared to be near to collapse. The building appeared to have timber-frame roofing that connected to masonry load-bearing walls. The walls had moved out of plane, pulling away from the roof, and were braced with strong-backs, as shown in Figure 4.21. Parapet damage was observed in the form of out-of-plane cracking at the base of the parapet, which led to residual deformation. Within the building, severe damage was observed to suspended ceilings, which were near to collapse. Bracing was being used vertically inside of the building to support the roof. The pawn shop owners were in the process of removing the merchandise and closing the business. The pawn shop owners indicated that they were renting for \$4,200 per month and expected that the building owner would repair and try to re-lease. The building was irreparable, was eventually demolished, and is being rebuilt at the time of this report. On a few occasions, especially in Eagle River, damage warranted demolishing the building.

Another common damage pattern in CMU walls was the stepped- or “stair”-type diagonal cracking that in many cases caused partial failure of the wall (Figures 4.26, 4.27, and 4.28). The diagonal crack length ranged from a few CMU-unit lengths to covering the entire wall panel. Crack width ranged from hairline to severe cracking (2 inches wide). In some cases, vertical CMU wall cracks were the main damage (Figure 4.29). A common damage theme was masonry units crushing at the wall base, corners, and connections (Figure 4.30). Lack of seismic details at the connection between two orthogonal walls led to detachment and separation cracks between walls (Figure 4.24). Similarly, lack of reinforcement between CMU walls and columns led to detachment cracks at their interface (Figure 4.24). Vertical splitting, severe spalling, and crushing were observed in some CMU piers (Figures 4.28 and 4.29). Damage in lintels/headers was also observed. The lack of connection between the steel framing and the CMU wall led to deformation compatibility issues and damage at the wall-frame interface (Figure 4.31).



(a)



(b)

Figure 4.26. (a) Heavy CMU wall damage at King Tech High School and (b) steel beam–CMU wall connection failure in Central Middle School (photos: Anchorage School District).



(a)



(b)

Figure 4.27. CMU wall stepped cracking (photos: (a) Chris Motter and (b) JBER).



Figure 4.28. Damage in masonry walls, including damage at interfaces of perpendicularly oriented walls (photos: Chris Motter).



(a)



(b)



(c)



(d)

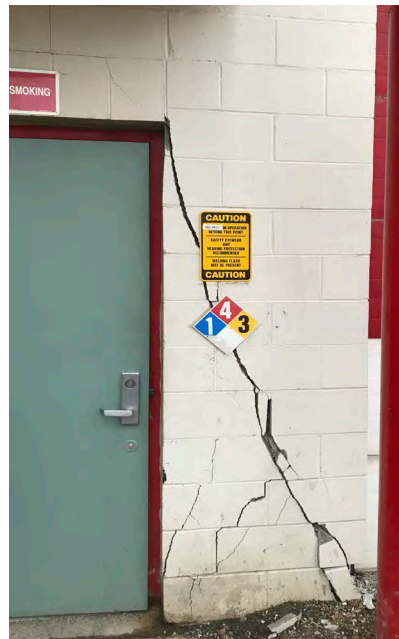
Figure 4.29. (a, b) Severe damage/dislodging of CMU wall (photos: (a) JBER and (b) DNR), (c) CMU vertical splitting (photo: DNR), and (d) CMU wall-floor interface cracking (photo: JBER).



(a)



(b)

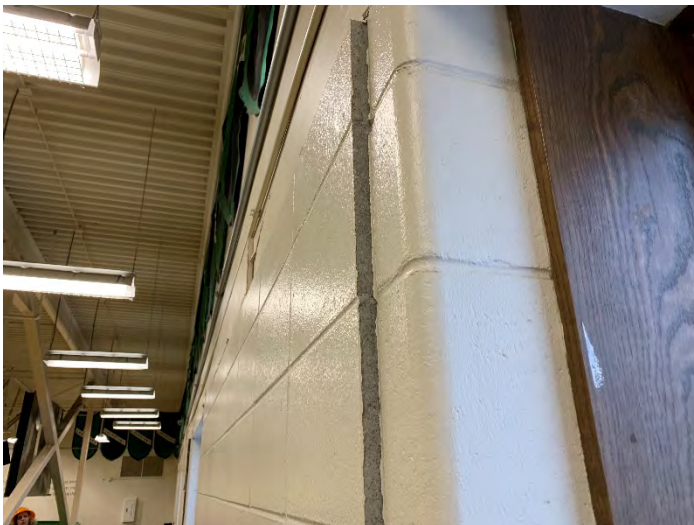


(c)

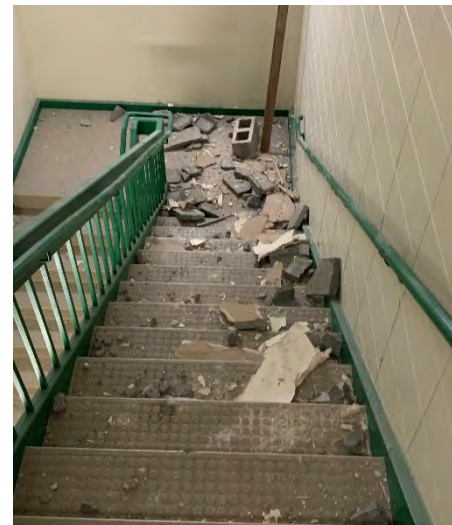
Figure 4.30. (a) Broken CMU at corners and shifted roof at Hyland Crest Booster Station in Eagle River (Photo: Anchorage Water and Wastewater Utility (AWWU)). (b,c) Heavy CMU wall damage at an Anchorage office building (photos: AWWU, MOA).



(a)



(b)



(c)

Figure 4.31. (a) CMU wall damage at the vicinity of a steel column because of lack of deformation compatibility and absence of ductile details and (b, c) falling CMU block hazard (photos: Wael Hassan).

Dislodged and fallen of CMU blocks due to shaking were also common during the inspections (Figure 4.31). In some cases, those fallen units represented serious life safety hazards, as they fell from large heights (35 feet) at the connection between the wall and floor or fell off severely cracked tall walls, even if these were classified as nonstructural walls. Other less common CMU failures included CMU and masonry chimney damage and fallen and CMU block foundation failure (Figures 4.32 and 4.33).



Figure 4.32. Masonry chimney partial collapse (photos: Janise Rodgers).



Figure 4.33. Severe masonry heater housing unit damage in Mat-Su (Photos Janise Rodgers).

4.7 Observed Damage in Wood Construction

Damage of residential wooden buildings, especially single-family units, varied widely on the basis of location. Structural damage in the Anchorage Bowl was much less significant than in the Northern Communities, especially in Eagle River, which suffered widespread structural damage due to lack of building code enforcement, as detailed in previous sections of this report. Because code compliance and building inspection is optional in the Northern Communities, the magnitude of the problem of non-engineered buildings is not precisely known; however, the substantial structural damage during the earthquake, which is a relatively short-duration deep event smaller than the design earthquake, is a good indicator that the Northern Communities' non-engineered, non-inspected buildings may be at higher risk of severe seismic damage (or even collapse) during a more significant event, which may cause serious human and economic loss. The comparison performed in Section 4.2 indicated that the Northern Communities suffered 18–20 times more damage than Anchorage relative to respective building stock size. Girdwood and Turnagain did not suffer notable structural damage in wood-frame buildings.

In the Anchorage Bowl, most of the structural damage in wooden buildings was due to geotechnical problems, non-engineered attachments such as external balcony decks and driveway sheds, and relatively older buildings constructed prior to the 1990s, when the MOA was able to fully enforce building codes and inspections in the Anchorage Bowl (David Sheer, Ross Noffsinger, et al., pers. comm., 2019). Modern buildings engineered after 1994 suffered only cosmetic drywall cracking in most cases. There were major concerns about the quality of construction in the Anchorage Bowl and the Northern Communities during the construction boom from 1975 to 1987 (David Sheer, Ross Noffsinger, et al., pers. comm., 2019), and these were proved to be valid concerns by the poor performance of buildings built in that period in Anchorage and the Northern Communities during the November 2018 earthquake. However, even new buildings in the Northern Communities performed poorly, as indicated above. In general, residential wooden buildings in Anchorage performed much better than in the Northern Communities.

Mat-Su suffered significant structural damage to some residential wooden buildings and businesses, heavier than Anchorage Bowl, as seen from Figures 4.9–4.14. About 19 residential wooden buildings and 4 businesses suffered major structural damage or collapse. The prevailing shaking intensity in Mat-Su is believed to be about 0.3g, similar to that of Anchorage, yet causing more significant damage possibly due to lack of code enforcement in Mat-Su. An example house on the Finger Lake shore in Mat-Su Valley is seen in Figure 4.34.



(a)



(b)

Figure 4.34.a. Examples residential building damage in Mat-Su (photos: (a) Chris Motter and (b) Wael Hassan).



Figure 4.34.b. Example of inside damage to a residential building in Mat-Su (photos: Chris Motter).

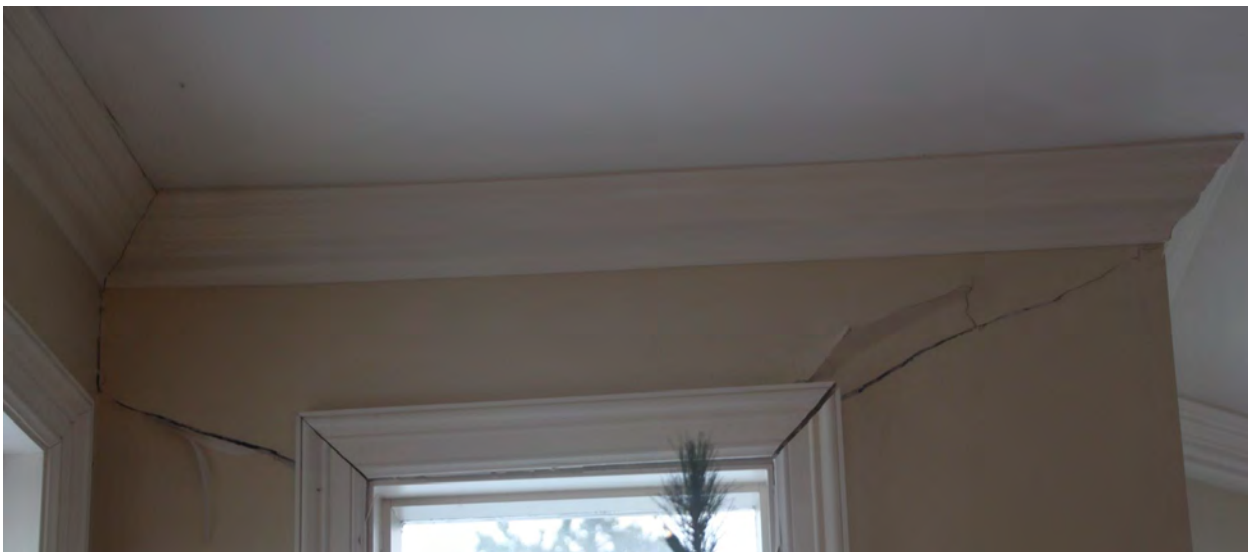
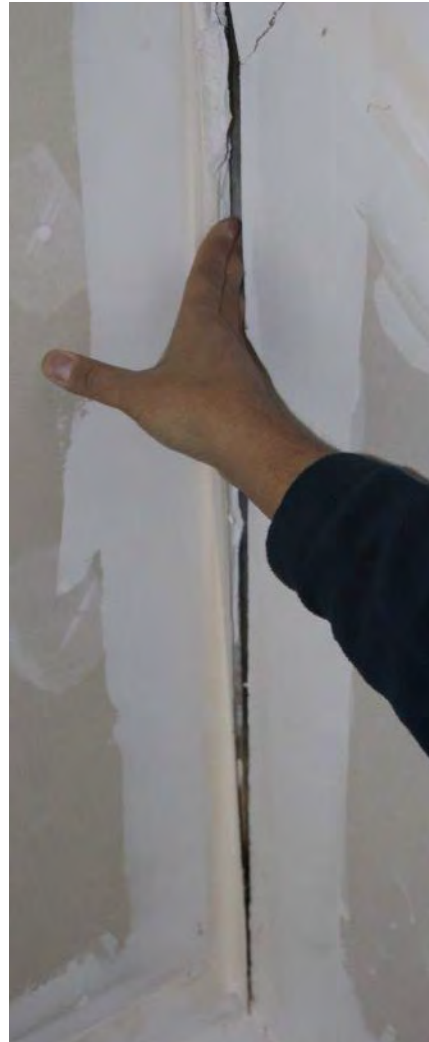
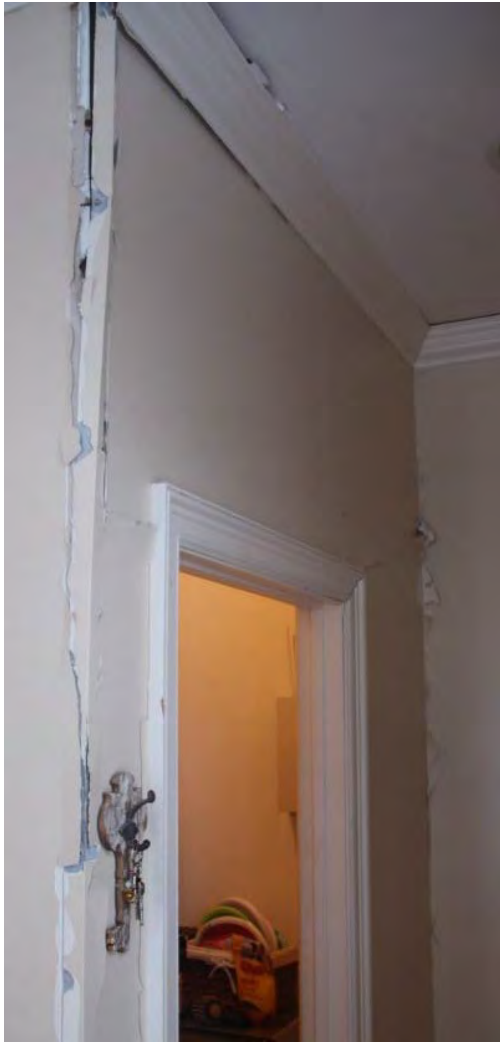


Figure 4.34.c. Example of inside damage to a residential building in Mat-Su (photos: Chris Motter).

Damage to single-family residential buildings' foundations and crawl spaces was commonly observed because of soil failure and settlement. A statistic by a local engineer, Thomas Keats,¹⁶ showed that 92% of home damages were due to settlement of 50 homes built between 1970 and 1986 in Girdwood, Eagle River, Chugiak, Palmer, and Wasilla and showed that many of these residential buildings were structurally underdesigned or deficient.

Common damage patterns observed throughout included damage to crawl-space posts and connections (Figures 4.35 and 4.36), foundation damage and differential settlement (Figures 4.37 and 4.38), permanent residual drift in single-story residential buildings (Figures 4.20 and 4.38), exterior sheathing damage (Figures 4.34 and 4.35), interior/partition-wall movement, permanent drift of parking sheds and balcony decks, and detachment from main residential structures (Figure 4.20), shear wall failures and deflections (Figures 4.34, 4.35, and 4.39), major diagonal wall cracking indicating serious structural damage (Figure 4.39), wall-foundation interface uplift/sliding/offset, detachment at wood wall corners, and detachment of floors from exterior walls (Figures 4.20, 4.34, 4.38, and 4.40). In particular, shear walls with small aspect ratios suffered the most damage (Figure 4.34).



Figure 4.35.a. Shear wall damage in wood-frame residential buildings in Eagle River (photos: PND Engineers¹⁷).



Figure 4.35.b. Shear wall damage in wood-frame residential building in Eagle River (photos: PND Engineers).



Figure 4.35.c. Residential building damage in Eagle River (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)



(f)



(g)

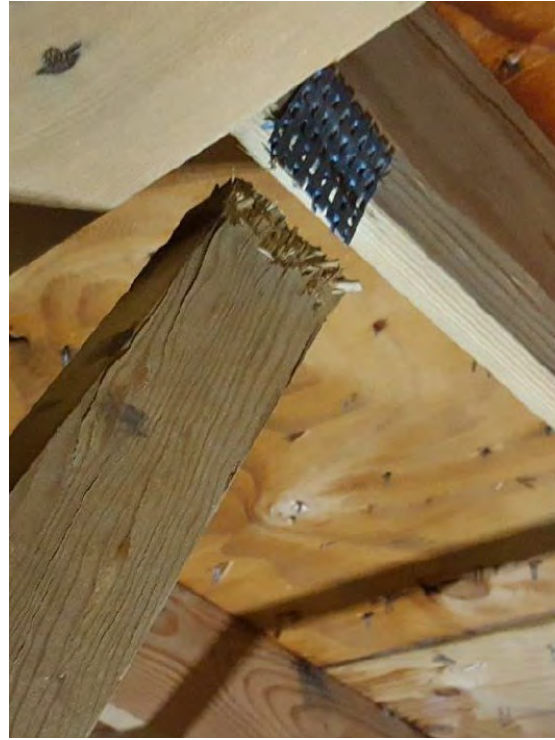


(h)

Figure 4.35.d. Example of residential single-family wood building attachment damage in (a-e, g) Anchorage and Eagle River (photos: MOA), (f) Eagle River (photo: Wael Hassan), (h) Eagle River (photo: Chris Motter).



(a)



(b)



(c)

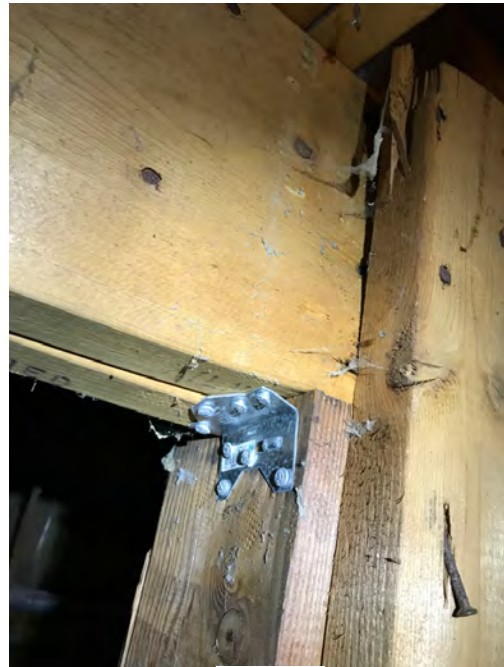


(d)

Figure 4.36a. (a) Wooden post connection damage at an office building in Eagle River (photo: Wael Hassan), (b) crawl space after damage (photo: Bart Meindhurdt), (c) crawl-space connection damage (photo: PND Engineers), and (d) parking-shed connection damage in Eagle River (photo: Wael Hassan)



(a)



(b)



(c)



(d)

Figure 4.36b. (a-d) Example of residential single-family wood building crawl space and foundation damage (photos: MOA)



(a)



(b)



(c)



(d)

Figure 4.36c. Examples of foundation wall damage in residential wood buildings (a, b photos: MOA); (c) Porch foundation damage in a wood residential building in South Anchorage (photo: Wael Hassan); and (d) Foundation wall damage in and Eagle River office building (photo: Wael Hassan).



(a)



(b)



(c)

Figure 4.37. (a) Damage to residential wood building in Anchorage (photo: West et al. 2019) and (b, c) building detached from garage because of soil failure (photos: Wael Hassan).



Figure 4.38.a. Residential building damage in Eagle River (photos: Chris Motter).



Figure 4.38.b. Residential single-family housing severe shear wall and nailed-connection sliding/uplift from foundation damage in a residential building in Anchorage (photos: MOA).



Figure 4.39. Severe shear wall and nailed-connection damage in a residential building in Anchorage (photos: Wael Hassan).



(a)



(b)



(c)

Figure 4.40. Partial collapse of a residential building in Eagle River related to uncompacted fill failure (photos: (a) Loren Holmes and (b, c) Geotechnical Extreme Event Reconnaissance¹⁸).

The sources of structural damage observed in non-engineered and older buildings, especially in the Northern Communities, stemmed primarily from known deficiencies that can be summarized (nonexhaustively) based on EERI inspections, personal interview and communications with local engineers (David Sheer, Ross Noffsinger, et al., pers. comm., 2019), ASHRAE/IAPMO Earthquake Panel (2019), and Horazdovsky et al. (2019) as follows:

- absence of strapping or bolting of the superstructure to the foundation,
- absence of blockings in floor joists,
- underdesign/insufficiency of floor joists,
- uncompacted or poorly compacted fills leading to differential settlement,
- absence or insufficiency of shear walls,
- absence of shear wall nailing or use of cheap or insufficient nailing or staples,
- underdesign or nondesign of shear walls in wall thickness or number or size of nails,
- splitting and separation of sill plates,
- crawl-space connection problems,
- absence of defined shear walls to enable installing large windows,

- absence of defined fasteners,
- absence of tie-backs for ledgers,
- tall foundation walls without restraint,
- the hillside building problem; poor design and construction of hillside building on steep grades,
- variable-height unsupported foundation posts on steep-grade parcels,
- extensive use of staples most of the time instead of nailing throughout an entire building, and
- absence of bracing walls to detached garages.
- Not involving engineering design or inspection in the process

A severe example is a 59-room hotel building in Eagle River built in 2003 on a sloped-grade parcel. There was significant crawl-space damage, and there were crushed floor joists, as they did not have blockings. Straps and hold-down ties were also missing on the exterior perimeter, so the building was not tied to its foundation, which means the building did not have seismic resistance to rocking, uplifting, or sliding. Such an example constitutes a public hazard that should be treated with legal action. It should not be optional for owners of public facilities, commercial buildings, and the like to choose whether to follow building codes in design and construction and have their building inspected during construction. Users of such buildings in actively seismic regions assume these buildings are seismically resistant and designed to comply with relevant building codes. Legislation following the California example may be recommended to address this problem, by having immediate simplified or thorough seismic assessment of public and commercial buildings in the Northern Communities and by enforcing the posting of warning signs of increased seismic collapse risk or retrofitting the building instead. During inspections by the EERI team and based on information from other teams of structural engineers (David Sheer, Ross Noffsinger, et al., pers. comm., 2019), it was noticed that many houses in the Northern Communities did not have blueprints or that the owners had purchased generic \$500 blueprints online and slightly modified them to fit their space without involving any engineers in the process. This resulted in houses without lateral load-resisting systems. Many homes were damaged because of this practice, and some were on the verge of collapse. It is the opinion of the authors of this report, based on the observation of the level of structural damage in the Northern Communities due to this “less than DBE earthquake,” that a future MCE-level event would cause major destruction to non-engineered buildings and potential human loss within the Northern Communities.

4.8 Performance of Steel Buildings

From a structural-damage viewpoint, steel buildings performed the best during the November 2018 earthquake. The EERI team rarely encountered any structural steel damage during inspections, except a few sporadic cases. The Anchorage School District reported a few isolated incidents of bolt loosening, weld and anchor failures and minor bracing buckling. However, heavy nonstructural damage and ground failure-related structural damage were evident in many cases. A common structural damage pattern was damage related to the connection to brittle material, such as the unseating of a steel floor joist, beam, or truss from a concrete- or CMU-bearing wall, as presented in the previous section. As indicated earlier, CMU walls or other wall infills that are not attached to structural steel columns led to major deformation incompatibility and, consequently, to major damage to the brittle material at the interface (Figure 4.31). However, no confirmed structural steel damage could be reported.

On one occasion, susceptible design errors may have led to steel-member foundation damage. This case was a two-story, light-gauge-steel office building constructed in 1974 that was retrofitted prior to the earthquake to upgrade its seismic resistance to code level. The seismic upgrade featured several cross and single steel braces (Figure 4.41). Inspecting the earthquake damage revealed severe brace foundation damage, including major splitting cracks, concrete crushing, and base-plate grout-pad damage (Figure 4.41). There were no signs of geotechnical or ground failure inside or near the building site. Upon further investigation of the building and its structural drawings, it appeared that two of the building's original steel braces were present, and they were likely not accounted for when upgrading the building with new braces, which may have led to major eccentricity that possibly added unexpected seismic demand to the new braces, leading to brace foundation damage consistent with that observed. Another possibility is not accounting for bidirectionality effects when designing foundations that support seismic steel braces in two orthogonal directions.



Figure 4.41. Foundation damage and base plate grout pad crushing in several retrofit steel braces in the Anchorage office building. Bolts were loosened by the ground motions on several base plates. No evidence to support soil problems at the area and the damage is believed to be due to retrofit system design errors. (photos: Wael Hassan)

Another expected observation was the heavier nonstructural damage in stiff steel buildings. The case of the University of Alaska, Anchorage (UAA) campus, is worth presenting. Two neighboring four-story steel buildings on campus, the Engineering and Industry Building (EIB) and the Health Sciences Building (HSB) that were connected by bridge experienced similar 0.21g PGA but responded with significant difference in terms of nonstructural damage, despite similar soil conditions, age (2016), nonstructural system restraints, and building height. The only difference was that the EIB had a steel moment-frame structural system, while the HSB had steel-braced frame system. The stiffer HSB building attracted more seismic forces, leading to moderate-to-heavy nonstructural damage and water flooding, while the EIB suffered only negligible cosmetic nonstructural damage.

Several steel mid-rise and tall structures were investigated, including those built in the 1970s; however, no confirmed structural steel yielding, fracture, or buckling was observed. It is noteworthy, however, that in most of these buildings, the inspection did not include exposing possible vulnerable structural steel elements, such as pre-Northridge connections or base plates, and there is thus a possibility that hidden structural damage in vulnerable elements may have been missed, especially with buildings that experienced heavier nonstructural damage. In some cases, where heavy nonstructural damage and water flooding warranted exposing structural elements as a part of the repair process, the team was able to inspect some structural elements directly. This included the University of Alaska, Eagle River campus, where heavy shaking resulted in major nonstructural damage, water flooding, and partition-wall damage. In this building, it was suspected that minor yielding took place at one or two steel columns.

A typical case to present good structural mixed wood shear wall structural steel-floor building performance is a multistory, 2014 building for senior citizens in Eagle River (Figure 4.42). The building suffered significant sheetrock damage and moderate water flooding damage with an estimated repair cost of about \$602,000. The building is a 76,804-sq. ft., 56-unit senior-living facility with underground parking. The site footprint at garage level is approximately 18,900 sq. ft. The wood shear walls are supported at the ground level on a perimeter-reinforced concrete retaining wall. The ground grade on-site is rather steep, rendering the concrete wall to act as a shear wall for a large percentage of the building perimeter. Thorough inspection of the building revealed no structural damage to wooden walls or steel decks. However, a few concrete wall sections had vertical splitting and diagonal shear cracks (Figure 4.43). There was also some minor structural damage, such as some shear studs pultruded in a composite deck and minor crushing in wooden posts (Figure 4.42). Seismic and expansion joints in steel buildings performed as per the design intent, experiencing light-to-moderate nonstructural damage and protecting the structural elements.



(a)



(b)



(c)



(d)

Figure 4.42. (a) Eagle River senior-citizen facility with (b) beam-column connection drywall damage, (c) pultruded shear stud at a concrete-steel composite slab, and (d) bearing failure at the top of a wood post (photos: Wael Hassan).



(a)



(b)

Figure 4.43. (a) Retaining-wall cracking and (b) sheetrock damage in an Eagle River senior-citizen facility (photos: Wael Hassan).

In some cases, there were sporadic steel-member failures, but this did not represent a common theme, as in the Girdwood AWWU facility with its damaged steel crane beam (Figure 4.44), the Hilton Tower in Anchorage with its soffit-beam failure (Figure 4.45), and the two steel braces in a diaphragm of a warehouse in Mat-Su. Anchorage School District reported a few isolated cases of floor bracing damage (Figure 4.45).



Figure 4.44. (a) Girdwood Wastewater Treatment Facility operations building with a sheared steel crane beam not connected at one end (photo: AWWU); (b,c) Hilton Anchorage steel soffit-beam failure (photo: PND Engineers).

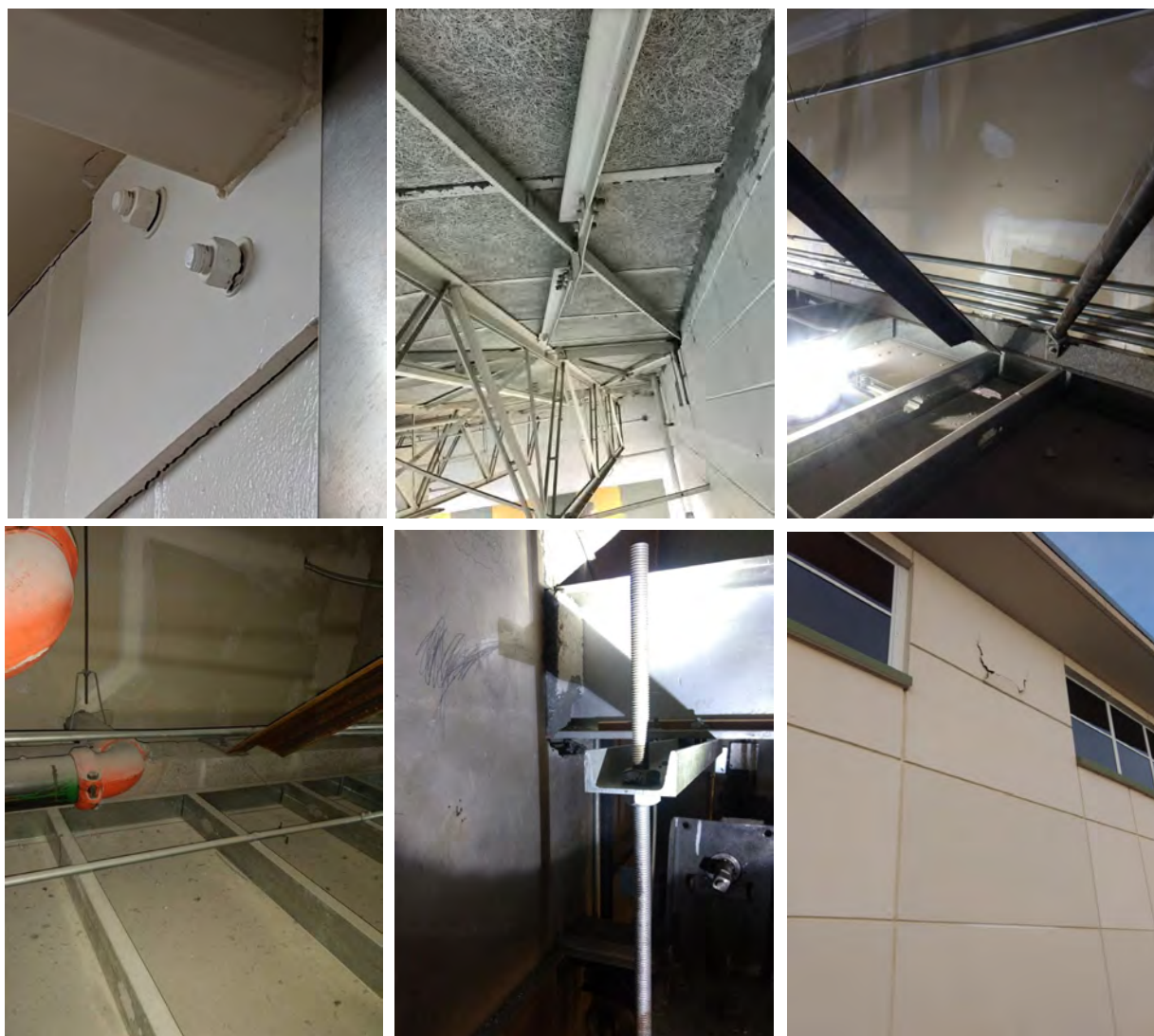


Figure 4.45. Steel component damage reported by Anchorage School District; (a) Bear Valley Elementary School strut bolts loosened in a connection with CMU wall; (b) Buckled X-bracing in Chugiak High School; (c) Failed weld and (d) Pull-out of a bolt at anchorage of ceiling lateral braces at Mirror Lake Middle School in Chugiak; (e) I-beam to wall interface in Gymnasium in West High School, Anchorage; and (f) damage visible in an exterior view of the I-beam interface; (photos a-f: Reid Middleton, ASD)

4.9 Performance of Instrumented and Tall Buildings

Seven instrumented buildings in Anchorage experienced light-to-moderate nonstructural damage and minor structural damage. Most ground-motion spectra recorded at the instrumented buildings were smaller than the DBE spectra. Records were successfully retrieved from all buildings except for the Port Access Bridge, whose damage was not recorded because of hardware problems.

4.9.1 Robert Atwood Building

The 21-story Robert Atwood building (Figure 4.46), a 1983 downtown Anchorage building with a steel shear wall core and steel moment frames, houses the main government functions and offices in Anchorage. The building is heavily instrumented by the U.S. Geological Survey (USGS) (Çelebi, 2006)¹⁹ for its height, structural-system significance, location, and special underlying soil conditions. Figure 4.47 shows a schematic of the instrumentation scheme, a 32-channel structural array and a 21-channel free-field and downhole-site array. Each of the instrumented 10 floors is equipped to record response motion in the east-west (EW, HNE) and north-south (NS, HNN) directions, while vertical response is monitored only in the basement. The HNN response is measured in the west and east sides, while the HNE

response is recorded in the east side only. The maximum recorded roof acceleration was $0.44g$ in the HNE direction, while the maximum recorded PGA was $0.21g$. Çelebi (2020) extracted from the records an NS fundamental period of 2.27 seconds, an EW period of 2.7 seconds, and a torsional period of 23.26 seconds. He also reported a maximum interstory-drift ratio of about 0.4%, “averagely estimated” from roof drift, which suggests no inelastic response (Figure 4.48). He also reported a beating effect from the recorded time history (Figure 4.48).



Figure 4.46. Atwood Building and USGS site array (photos: Wael Hassan).

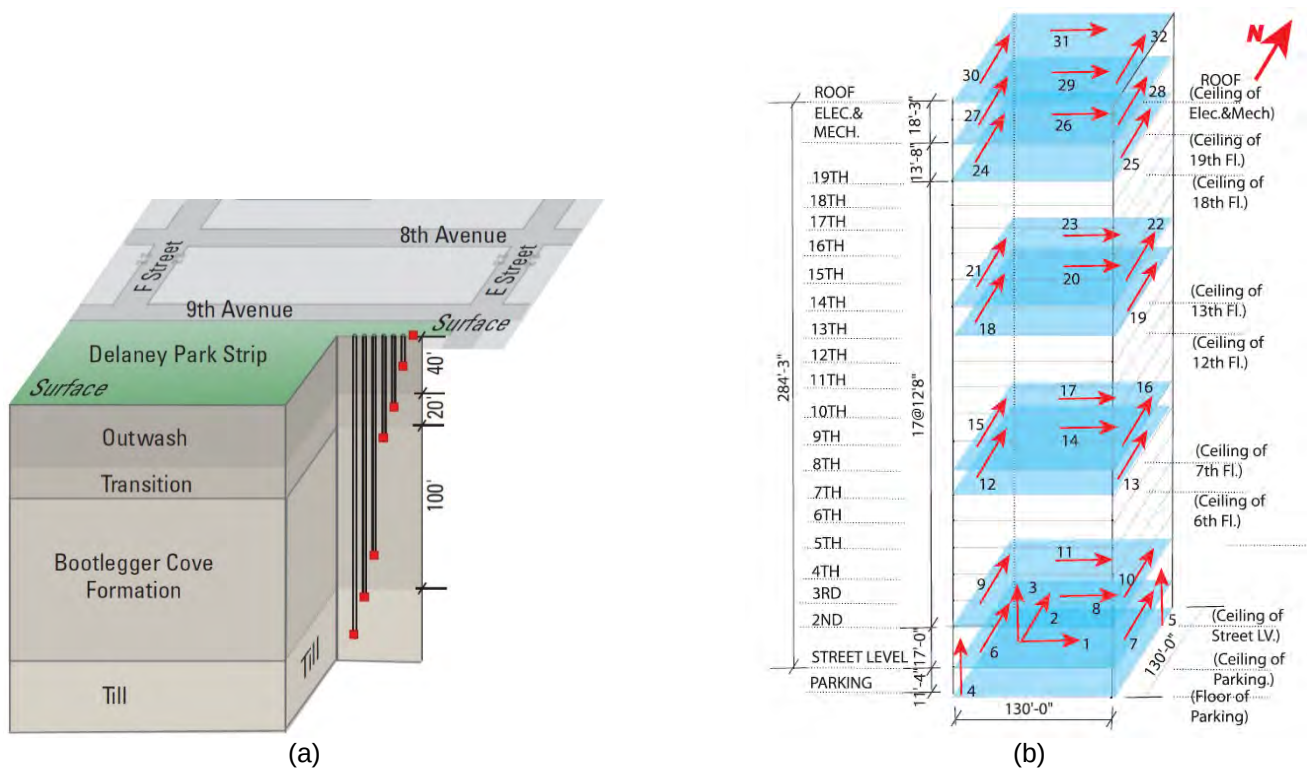


Figure 4.47. (a) Delaney Park free-field and downhole arrays and (b) Atwood Building sensor structural array (source: Çelebi, 2006).

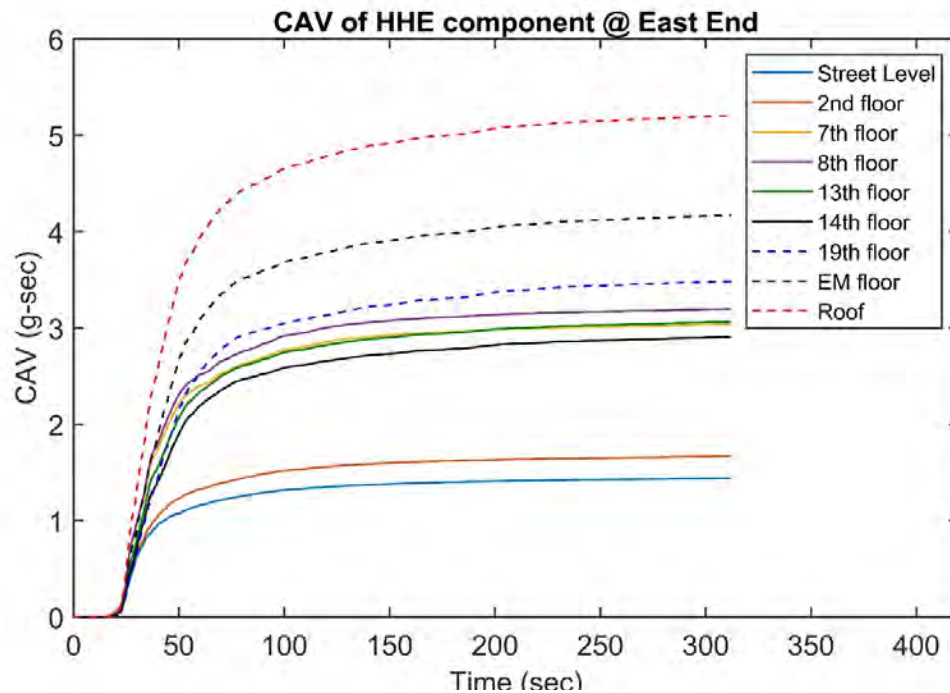


Figure 4.48. Atwood Building (a) roof acceleration and (b) drift-time histories (source: Çelebi, 2020). (c) CAV prediction of Atwood Building damage location of HHE component (source: Muin et al., 2018²⁰).

The building did not have any visible structural damage. However, it had water flooding and ceiling damage at one floor because of two piping-connection failures in the mechanical room (Figures 4.49 and 4.50). In addition, suspended-ceiling grid and tile failure occurred at three floors. Unrestrained furniture damage and overturning occurred at many floors (Figure 4.49). The building was yellow-tagged. Inspecting the roof fixtures and connections of the heavy heating, ventilation, and air conditioning and communication equipment/appendages did not reveal any damage related to the earthquake.



(a)



(b)



(c)



(d)

Figure 4.49. Nonstructural damage at Atwood Building: (a) unrestrained bookcases and cabinets toppling and (b–d) ceiling tile and grid failure at various floors (photos: Wael Hassan).



Figure 4.50. Mechanical-room piping failure and water flooding at Atwood Building (photos: Wael Hassan).

A structural health-monitoring model analysis of the Atwood Building using the November 2018 earthquake record by Muin et al. (2018), published in a Structural Engineering Extreme Event Reconnaissance (StEER) report and based on the cumulative absolute velocity (CAV) method developed by Muin and Mosalam (2017),²¹ was able to successfully

predict nonstructural damage at three floors, matching the floors with observed damage (Table 4.1 Recorded Atwood building accelerations (source: StEER, 2018)²⁰, Figure 4.48).

Table 4.1 Recorded Atwood building accelerations (source: StEER, 2018).

Floor	HNN-West	HNN-East	HNE-East
Street level	0.17g	0.23g	0.22g
2nd	0.17g	0.26g	0.26g
7th	0.22g	0.28g	0.31g
8th	0.22g	0.28g	0.33g
13th	0.18g	0.18g	0.25g
14th	0.17g	0.18g	0.23g
19th	0.19g	0.17g	0.23g
EM	0.22g	—	0.33g
Roof	0.33g	0.41g	0.44g

4.9.2 Frontier Building

The 14-story Frontier Building (Figure 4.51), a 1981 concrete building with a moment-resisting frame, is instrumented by the USGS as shown. The recorded PGA was 0.193g, and the maximum recorded peak roof acceleration was 0.223g. Based on the recorded motion, Çelebi (2020) estimated the fundamental periods as 2.22 seconds (NS), 2.94 seconds (EW), and 1.72 seconds (torsional). He also estimated the maximum drift to be about 0.4%, based on “average estimated” roof drift, which indicated no nonlinearity. Figure 4.52 shows roof acceleration, displacement, and drift-time histories, as well as amplitude spectra.

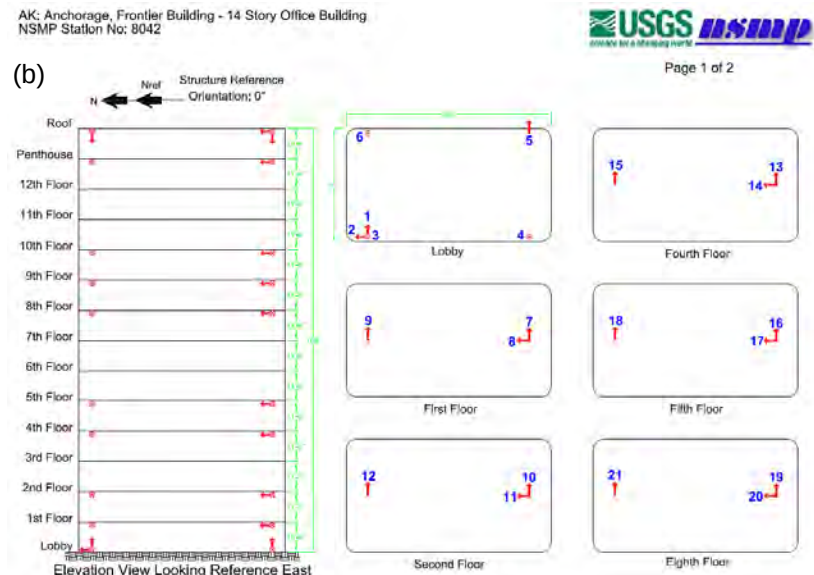


Figure 4.51. (a) Frontier Building and (b) its seismic sensor array (photo: (a) Wael Hassan; source (b) USGS).

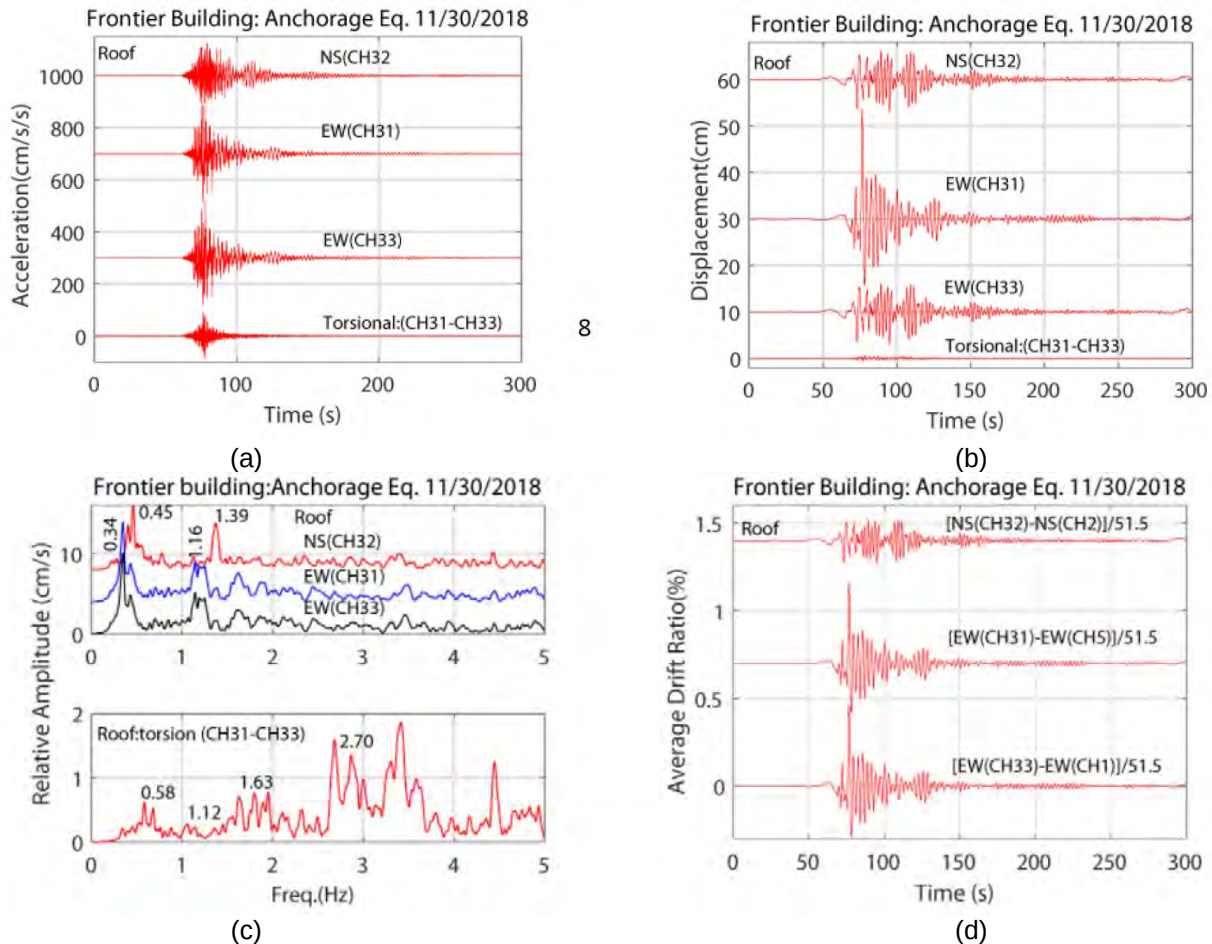


Figure 4.52. Frontier Building's (a) roof acceleration and (b) displacement-time histories, (c) roof amplitude spectra, and (d) "average estimated" drift-ratio history (source: Çelebi, 2020).

The building experienced light, nonstructural ceiling and partition-wall damage with no water damage (Figures 4.16, 4.53, 4.54, and 4.55). Stairwell sheetrock panels cracked in floors one through six, with some long, wider diagonal cracks in the sheetrock of stair walls at floors two and three. The building is relatively stiff, and it did not experience noticeable mechanical, electrical, and plumbing damage. Very few ceiling tiles fell, some ceiling grids were kinked, and some interior-partition walls cracked vertically, especially at lower levels. In all floors, the drywall separated from exterior and corner concrete columns. Two of their elevators went out of service because of counterweight and elevator-alignment problems. The only notable structural cracks are structural concrete-cover vertical-splitting cracks in most exterior and corner columns at floors three to five, which are indicative of overstress of these columns perhaps due to seismic overturning axial loads. These cracks ranged in width from 1/32 to 1/16 of an inch. Columns at floors one and two did not experience these cracks. A separate concrete parking structure on-site did not have any damage.



Figure 4.53. Third-floor column-head finish cracks; cracks in gypsum ceilings could potentially indicate hidden floor-diaphragm damage (photo: Wael Hassan).



(a)



(b)

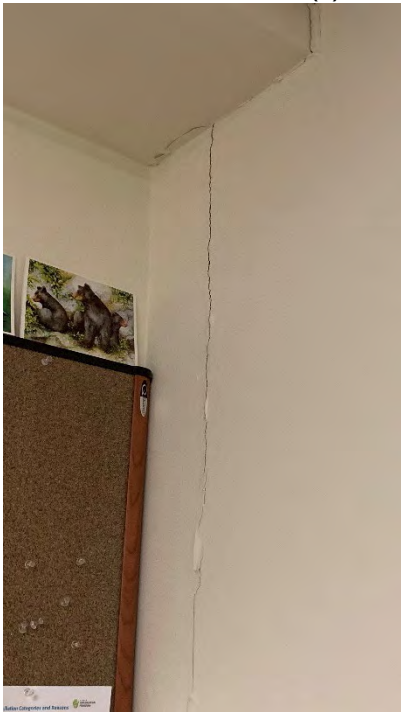
Figure 4.54. Frontier Building: (a) Elevator out of service because of counterweight damage. (b) Fifth floor electric after residual drift (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)



(f)



(g)

Figure 4.55. Frontier Building; (a) Third-floor ceiling damage, (b) partition-wall separation, (c–e) sheetrock cracks, and (f, g) typical stairwell drywall damage at third and fifth floors (photos: Wael Hassan).

4.9.3 British Petroleum Exploration Building

The British Petroleum (BP) Exploration Tower is a 14-story, steel moment-frame building that was constructed in 1985 (Figure 4.56). This tower is instrumented with USGS sensors at the ground, 8th, and 14th floors only. The recorded acceleration at the ground level was $0.2g$. The BP complex includes a three-story, low-rise building connected to the main tower with a sky bridge at level two (Figure 4.57).

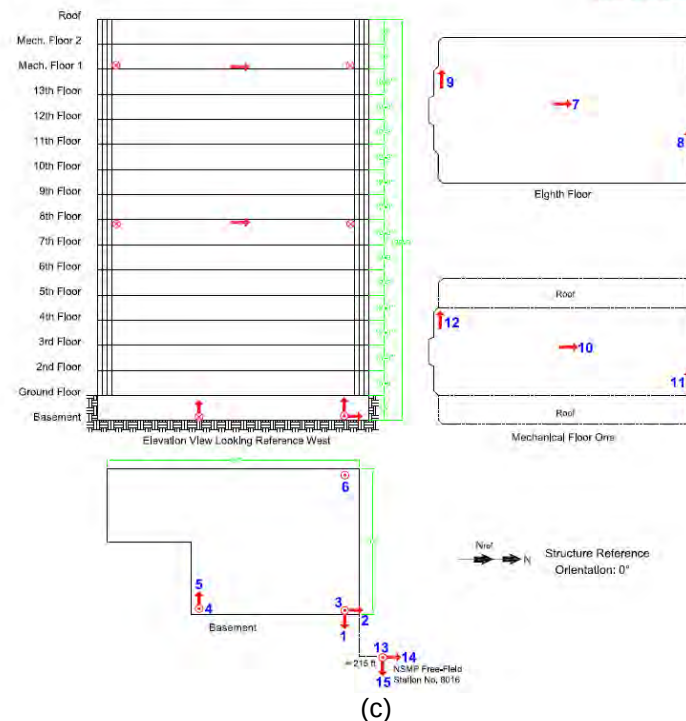


(a)

AK; Anchorage, BP Building - 15 Story Office Building
NSMP Station No: 8016



(b)



(c)

Diagram: 9/4/2013

Figure 4.56. (a) BP Tower (photo: Wael Hassan), (b) USGS sensors and recorders (photo: Wael Hassan), and (c) structural array instrumentation (source: USGS).



(a)



(b)

Figure 4.57. (a) Second-floor conference room with water damage from the third-floor mechanical room's connection failures in the low-rise building (photo: BP). (b) BP Tower and low-rise building (photo: Wael Hassan).

The BP Tower (Figure 4.58) experienced cosmetic nonstructural damage, water flooding, and some structural damage to staircases. However, the main structural elements did not experience any damage. The low-rise BP building also did not have noticeable structural damage. All four staircases in the main tower and the low-rise building had minor concrete cracking and some spalling and crushing in the corners, in addition to moderate sheetrock damage (Figure 4.57).



(a)



(b)



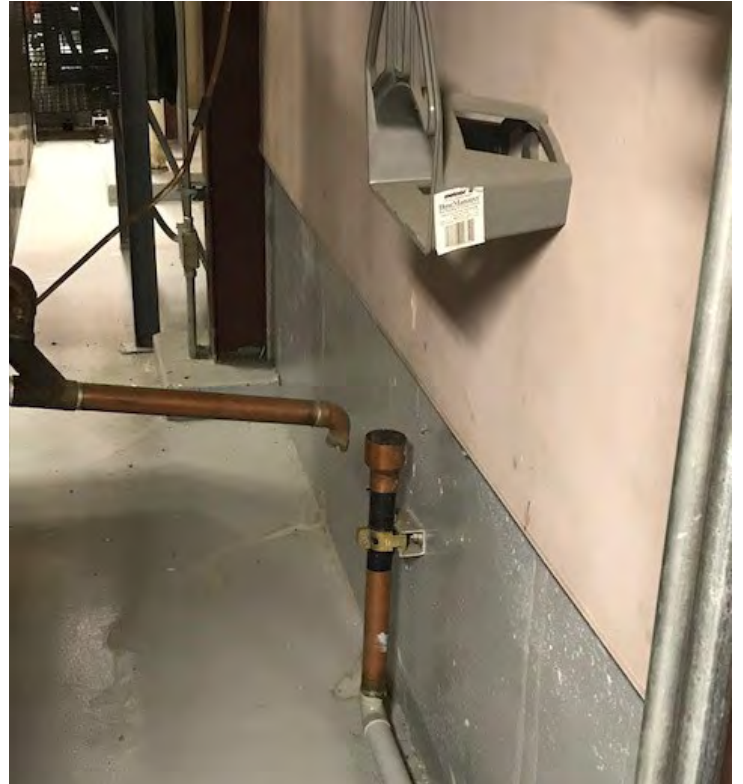
(c)

Figure 4.58. (a) Water and glycol flooding in the tower's ground-floor mechanical room; (b, c) tower stairwell concrete damage (photos: BP).

A water line broke in in the mechanical room on the third floor of the low-rise building, causing major water damage on the first two floors (Figure 4.59). Some nonstructural damage in light-gauge covers and in the ceiling tiles and grid occurred at several floors of the main tower and low-rise building. The sky bridge, with a seismic joint at the tower, experienced 2-inch displacement, leading to seismic joint damage and shattering of the bridge rail glass.



(a)



(b)

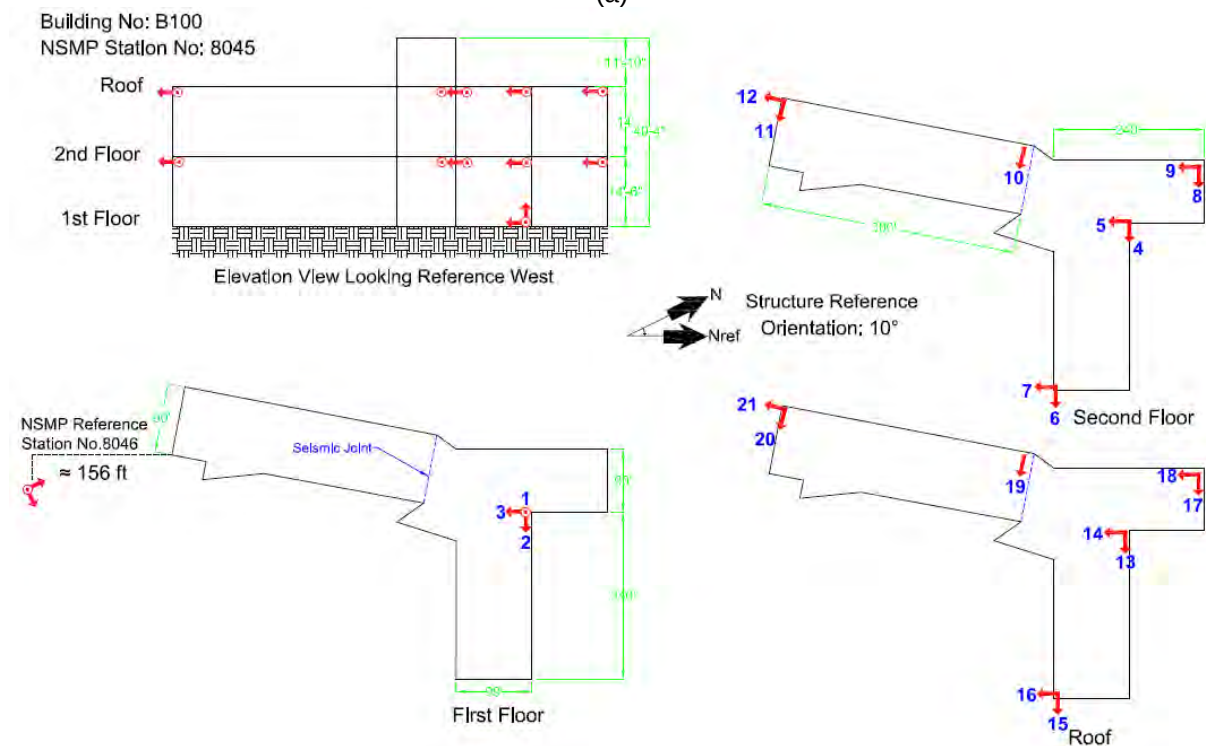
Figure 4.59. (a) Mechanical-room flooding and (b) pipe damage in the low-rise building (photos: BP).

4.9.4 Veterans Affairs Hospital

The Veterans Affairs (VA) Hospital is a two-story, steel moment-frame building in Anchorage, instrumented by the USGS (Figure 4.60). The hospital experienced only cosmetic and light nonstructural damage throughout the building but experienced some heavier ceiling-grid and ceiling-tile damage on the second-floor ceiling (Figure 4.61).



(a)



(b)

Figure 4.60. (a) VA hospital and (b) its seismic instrumentation (source: USGS).

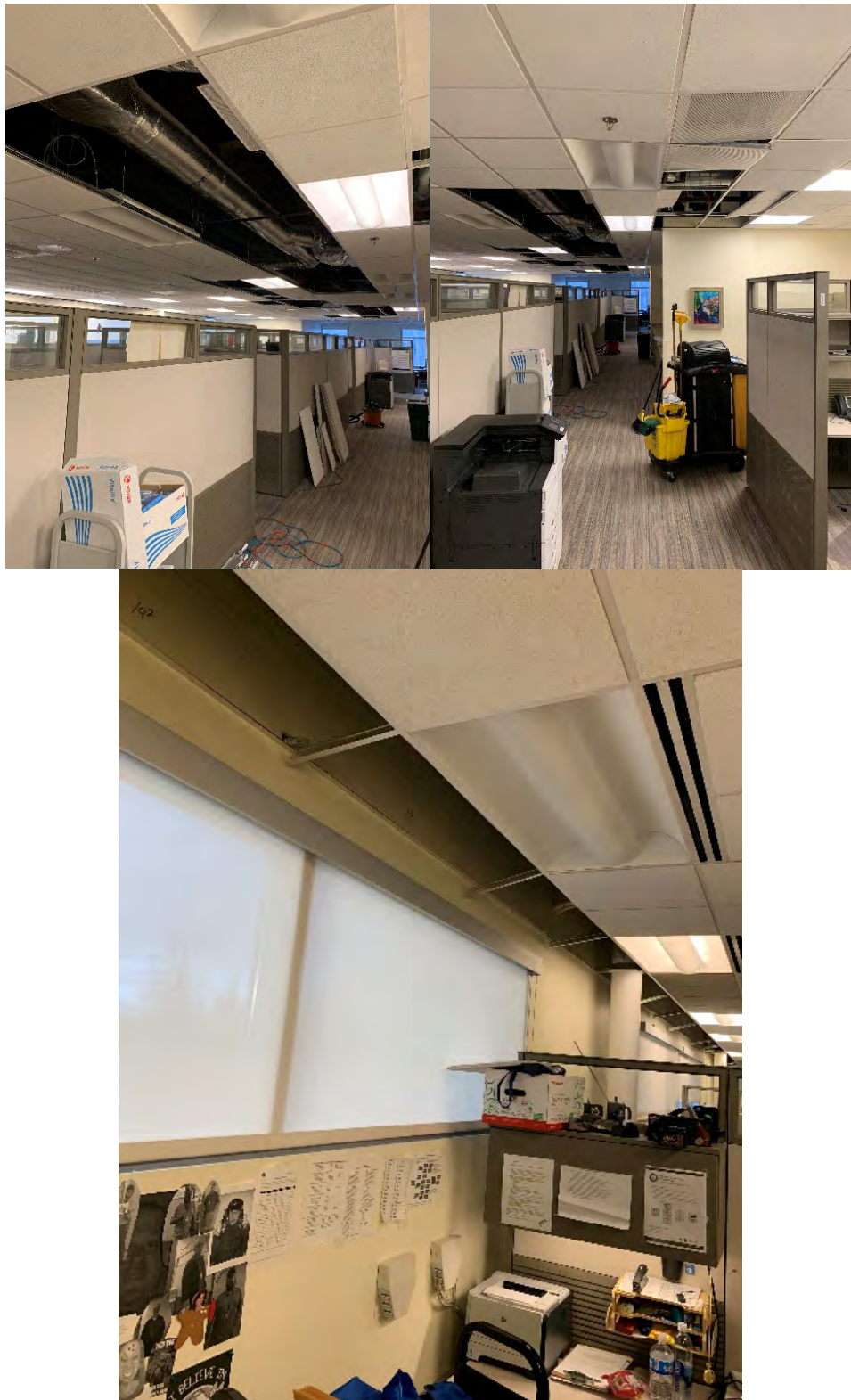


Figure 4.61. VA hospital second-floor ceiling damage (photos: Erol Kalkan).

4.9.5 The EIB

The EIB, a 2015 four-story steel moment-frame building at UAA campus (Figure 4.62) experienced only light cosmetic cracking in the sheetrock, especially at the stairwell, and breaking of one large glass cabinet (Figure 4.5). The building is instrumented on all four levels, along with a free-field site array outside the building. The maximum recorded PGA at the ground-floor level was 0.21g, and the roof acceleration was 0.58g. The recorded spectra at the building were lower than the DBE spectra at the building fundamental period (0.80 seconds), which explains the negligible damage.



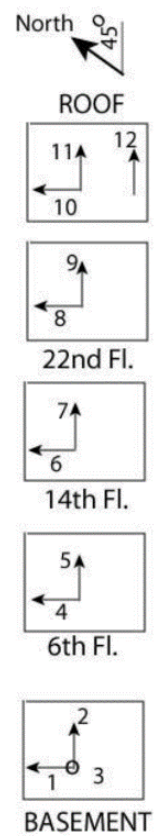
Figure 4.62. EIB, UAA, non-structural sheetrock damage throughout the building and a glass cabinet damage in the fourth floor (photos: Wael Hassan).

4.9.6 Hilton Tower

The Hilton Tower (Figure 4.63) is a 22-story, mixed-steel and steel-reinforced, concrete-composite construction built in 1971. The structural array consists of 12 accelerometers, some of which are triaxial, at five different levels. The building had minor nonstructural damage (Figure 4.64).



(a)



(b)



(c)

Figure 4.63. (a) Hilton Tower (photo: Wael Hassan), (b) instrumentation scheme (source: Çelebi, 2020), and (c) USGS data acquisition (photo: Wael Hassan).



(a)



(b)



(c)

Figure 4.64. (a, b) Hilton Anchorage steel soffit-beam failure (photos: PND Engineers) and (c) exterior-column finish failure (photo: Wael Hassan).

Çelebi (2020) processed the records of the M7.1 November 2018 earthquake in Hilton Tower. He reported NS and EW translational natural periods of 1 second for both directions and 1.35 seconds for the torsional period (Figure 4.65). He also reported an “average estimated” interstory-drift ratio of 0.35%, based on roof-drift interpolation, suggesting elastic response. The recorded PGA was 0.21g, while the peak roof acceleration was 0.65g.

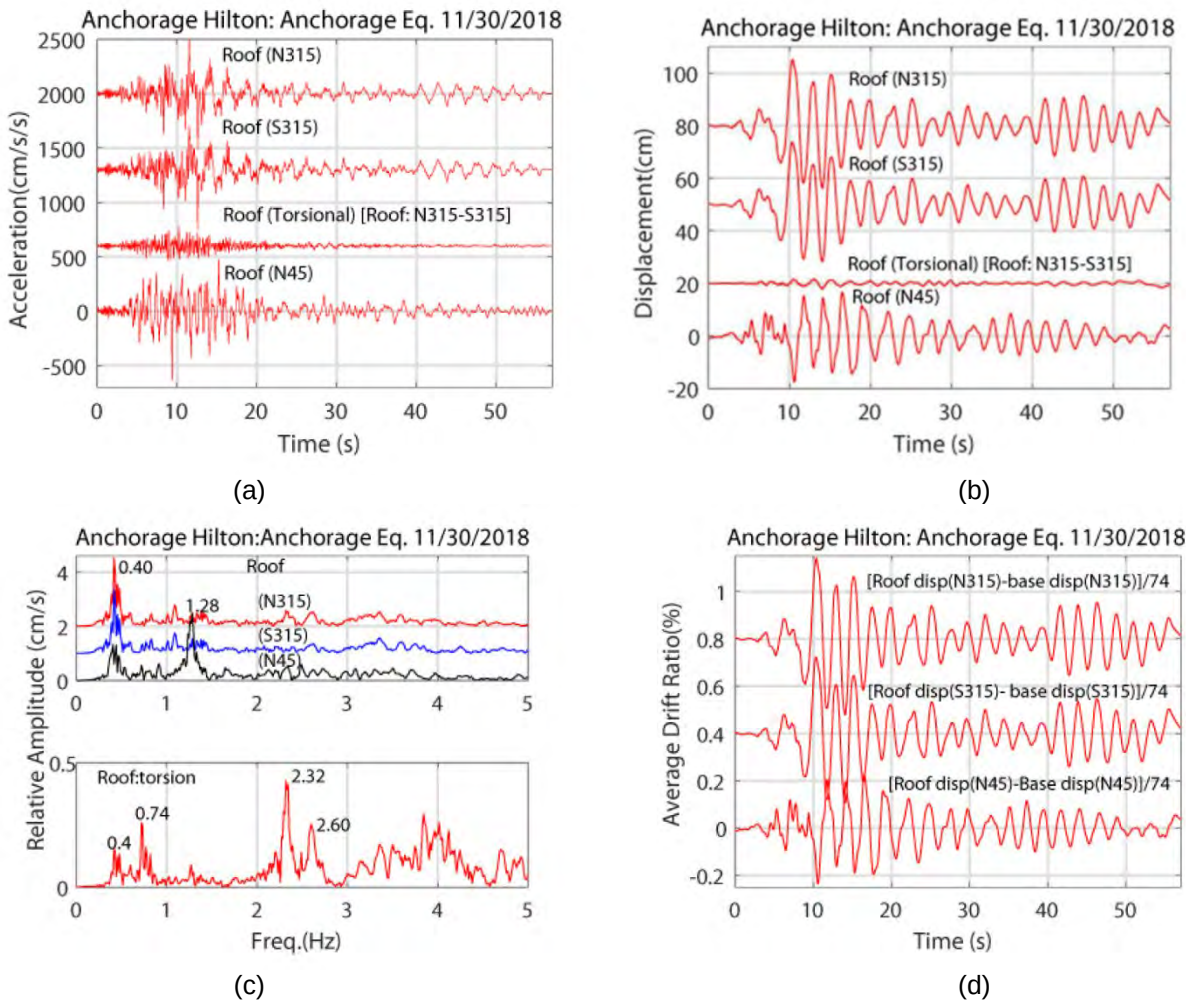


Figure 4.65. Hilton Tower's (a) roof acceleration and (b) displacement-time histories, (c) roof amplitude spectra, and (d) "average estimated" drift-ratio history (source: Çelebi, 2020).

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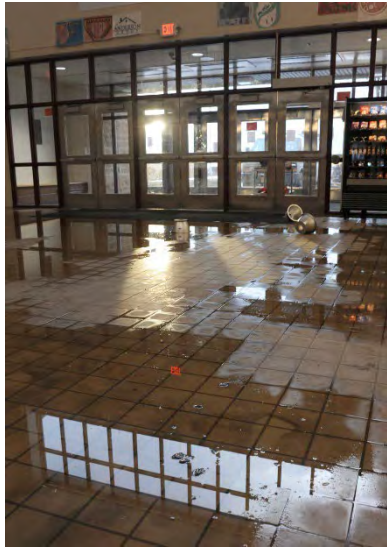
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5 NONSTRUCTURAL AND EQUIPMENT DAMAGE IN BUILDINGS

5.1 Overview

Widespread nonstructural damage was observed during the Earthquake Engineering Research Institute (EERI) Team reconnaissance following the November 2018 earthquake. The most common nonstructural damage observed, and the most disrupting to building function and costly to repair, was the water flooding due to fire-suppression system failure, water-boiler rigid piping failure due to boiler sliding, and mechanical-room water and glycol piping and connection failure (Figures 5.1, 5.2, and 5.3).



(a)



(b)



(c)



(d)

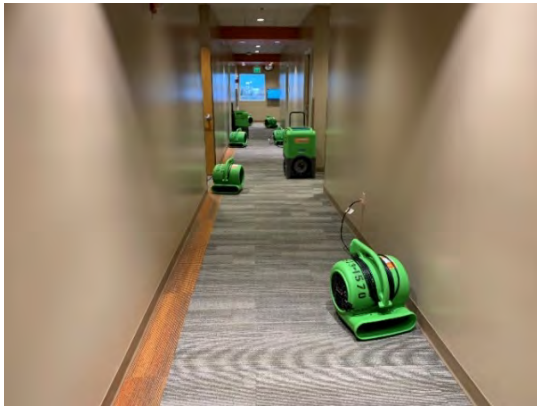


(e)



(f)

Figure 5.1. Examples of water flooding due to firefighting-system or heating-system failure: (a) an Anchorage school (photo: Anchorage School District (ASD)), (b) Alaska Airlines Center (photo: University of Alaska, Anchorage (UAA)), (c) office building (photo: BP), (d) glycol flooding at Gruening Middle School in Eagle River (photo: ASD), (e) Houston Middle School (photo: Matanuska-Susitna (Mat-Su) Borough School District), and (f) residential water damage (photo: Ben Meindhudt¹).



(a)



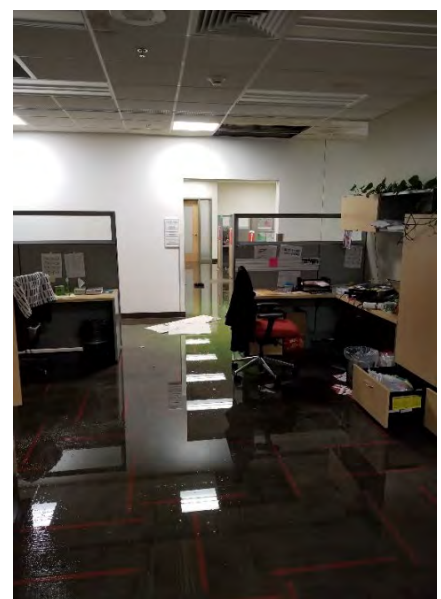
(b)



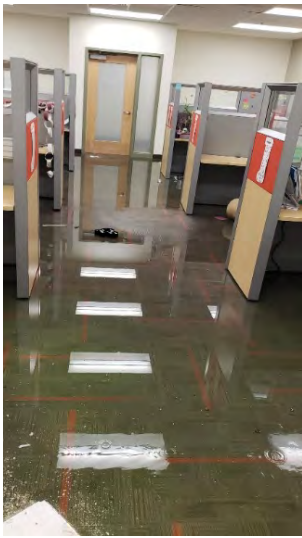
(c)



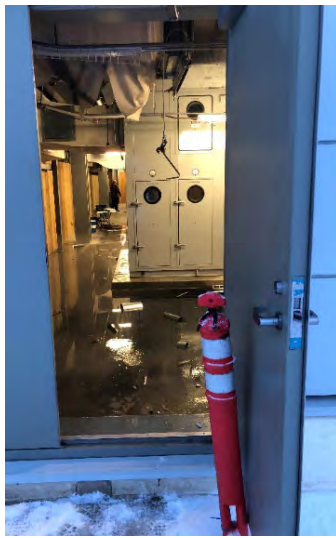
(d)



(e)



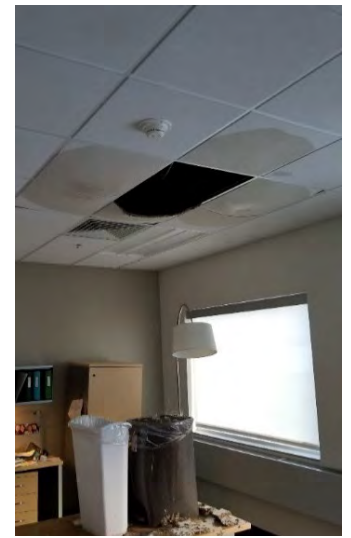
(f)



(g)



(h)



(i)

Figure 5.2. (a, b) Anchorage hospital blower drying after major sprinkler-system water flooding (photos: Wael Hassan), (c) Providence Alaska Medical Center (PAMC) Tower D water-sprinkler water damage (photo: PAMC), (d) Anchorage hospital with damaged ceiling and water-pipe connection failure (photo: Wael Hassan), (e) BBA glycol and sprinkler water flooding (photo: BBA), BBA water flooding at (f) office, (g) mechanical room, and (h) laboratories (photos: BBA).



(a)



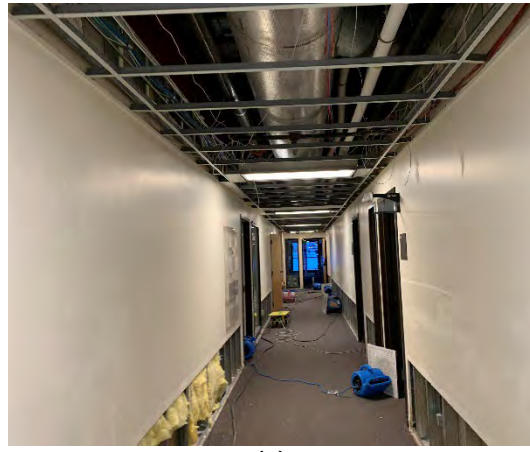
(b)



(c)



(d)



(e)

Figure 5.3. (a–c) Water-pipe connection damage at the Engineering and Computation Building, UAA; (d) water leaking through a wall at UAA Health Sciences Building (HSB) because of sprinkler pipe failure; and (e) UAA Eagle River campus ceiling damage and floor drying after major water flooding; notice that the bottom foot of drywall was water-damaged throughout (photos: Wael Hassan, UAA).

Other very common nonstructural damage patterns observed were glass façade and window failures in low-rise buildings, suspended-ceiling tile and grid failure in office and commercial buildings, cracking around openings and sheetrock/drywall cracking in all types of buildings, and overturning of tall furniture items, including bookcases and cabinets, which in most cases were not seismically strapped.

Less common nonstructural damage patterns observed were masonry-veneer cracking and failure; partition-wall damage ranging from light cracking to out-of-plane deformation and complete detachment from buildings; mechanical-equipment and heating, ventilation, and air conditioning (HVAC) duct failure due to poor restraint; internal boiler cracking; electrical panel failure due to water damage; and gas leaks due to connection failures of rigid gas pipes. In Mat-Su region, non-structural damage of all types was also widespread, especially in schools and low-rise buildings^{4,5}.

5.2 Water Damage (Piping, Tanks, and Firefighting Systems)

Water leakage and flooding was the most common nonstructural damage observed in office, commercial, hospital, and school buildings. It was also the most influential on building operation, and its resulting damage was the most expensive to repair. Water damage resulted from fire-suppression system failure, water-boiler rigid-piping failure due to boiler sliding, and mechanical-room water and glycol piping and connection failure. In most cases, water leaked through walls, floors, and elevator shafts (Figure 5.3), damaging several floors below the level of the failed component.

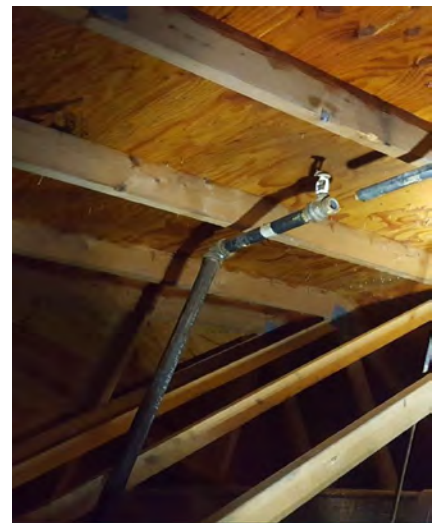
The first source of water damage was firefighting system failure. The Anchorage Fire Inspector¹ reported more than 200 firefighting system failures in Anchorage and Eagle River. The EERI team inspected many of these buildings with water flooding as a result of firefighting system damage. The most common root cause of firefighting system failure was rigidly connected sprinkler-head damage due to collision with other systems or interference with drop-ceiling panels (Figures 5.4 and 5.5), followed by rigid-sprinkler-piping connection/fitting failure due to poor restraint. In particular, rigid sprinkler pipes required restraint on a branch line if installed on rods smaller than 6 inches diameter⁶. In addition, thin, wall-threaded pipes suffered frequent damage. Collision of firefighting piping systems with orthogonal/different-plane neighbor systems was a common reason for failures. Long vertical hangers from the roof to lower ceilings led to significant movement of the ceiling and interacted with sprinkler pipes, leading to pipe and connection failure⁶. Hangers of pipes in older building not following spacing requirements failed, causing pipe damage. Another common pattern (according to the Anchorage Fire Inspector¹) was cloud ceiling movement against sprinkler piping. These two systems needed to be tied together to avoid pipe damage. The flexible sprinkler piping performed satisfactorily with minimum damage (Figure 5.5). The polyvinyl-chloride-pipe failure mode was mostly shear failure, while the metal-pipe failure mode was detachment at connections⁶. When branch lines were restrained properly in relatively newly engineered buildings, water damage was prevented. The Anchorage Fire Inspector¹ reported good performance of firefighting systems in buildings constructed after 2003.



(a)



(b)



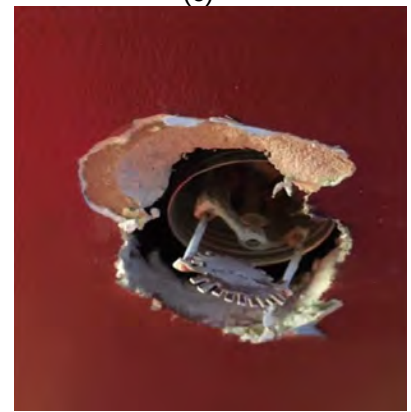
(c)



(d)



(e)



(f)



(g)



(h)

Figure 5.4. (a, b) Six-inch underground water main bent (code required four-inch annular space in place), (c) fitting cracks, (d) 1-inch pipe failure, (e) sprinkler-head failure due to collision with steel beam, (f) concealed sprinkler failure (photos: Bart Meinhudt¹), (g) concealed sprinkler failure (photo: Wael Hassan), and (h) sprinkler-head failure due to moving against and damaging drop-ceiling tiles; notice the ground-motion directional orbits generated by the relative movement (photos: Wael Hassan).



(a)



(b)



(c)

Figure 5.5. (a, b) Failed hangers of fire-suppression-system pipes and (c) flexible sprinkler head without damage during the earthquake (photos: Bart Meinhudt¹).

The second source of water damage was the failure of water boiler/tank connections to rigid pipes (Figures 5.6, 5.7, and 5.8). In most cases, water boilers were not seismically restrained either because of being in a non-engineered or non-inspected building or because of the large size of the boiler, which did not require restraint according to local codes. However, it should be noted that if the tank is not restrained, the code required piping connections to allow for several inches of movement, which implies the need to use flexible piping, essentially, with unrestrained tanks. The unrestrained-large-tanks provision in the code assumes the heavy weight of the tank will counterbalance the seismic overturning effect; however, many large tanks did slide several inches during the earthquake, causing major water flooding (Figure 5.6). Some local engineers reported that tanks with flexible connections moved more than those with rigid connections, causing leaks in the former ones. In many cases, straps of water boilers failed by pulling out because of insufficient bolting to the wall (Figure 5.6). It is important to note that the even with non-engineered straps/restraints provided by some building owners to their water tanks, many water-damage incidents were prevented. However, it seems that code provision language on unrestrained tanks being clearly tied to flexible piping is needed (Figure 5.9). It also seems that strict enforcement of the seismic design of water-boiler restraints in essential facilities is needed.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.6. Unrestrained water boilers atop the Westmark hotel slid 3.5 inches, shearing top pipe connections; hotel personnel indicated that tank tie-down was not required by code, as it exceeds 1,000 gallons. (a, b) Makeshift angle restraints were placed after the earthquake, (photos: (a) Wael Hassan and (b) PDC Engineers). (c) The water boiler at Mat-Su Regional slid a few inches, breaking the top gas-pipe connection (photo: Janise Rodgers); (d) The failed strap of a 70-gallon residential water boiler (photo: Wael Hassan). Hundreds of residential water leaks and gas leaks resulted from unrestrained or poorly restrained water boilers; (e) example of strap failures of residential water boilers (photo: MOA); (f) Strong shaking failed water boiler strap, sheared top pipe, and caused collision damaging heating duct (photo: MOA).



(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.7. (a) Glycol-heating-pump connection failure and glycol leak at Gruening Middle School, Eagle River; (b) boiler-room elbow-pipe connection failure and leakage; (c, d) hot-water-tank angle-bolt failure at Gruening Middle School; (e) water-boiler strap sliding (notice markings above the strap); and (f) poor-restraint angle failure of water boiler in a multistory building in Eagle River (photos: Wael Hassan).

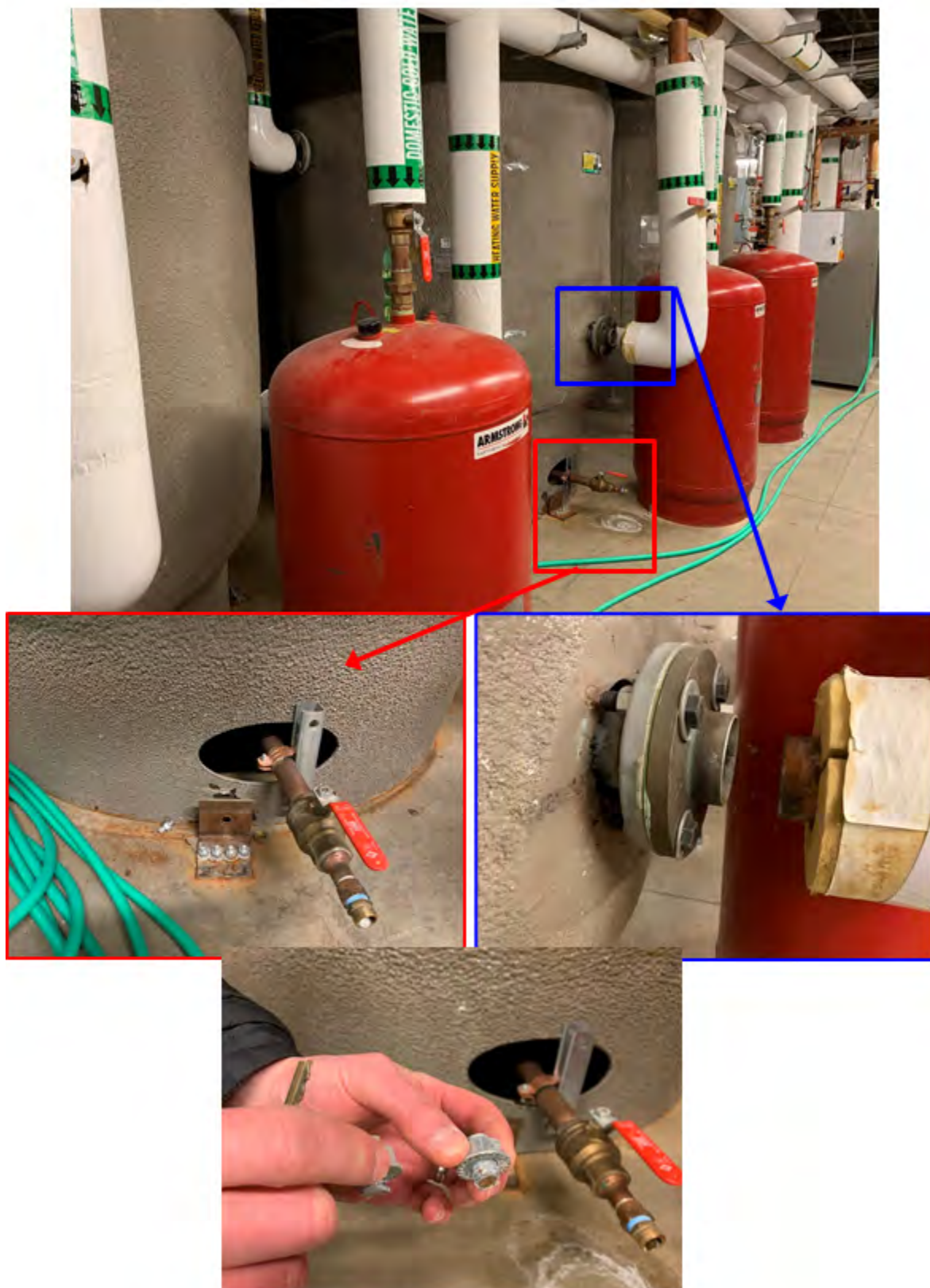
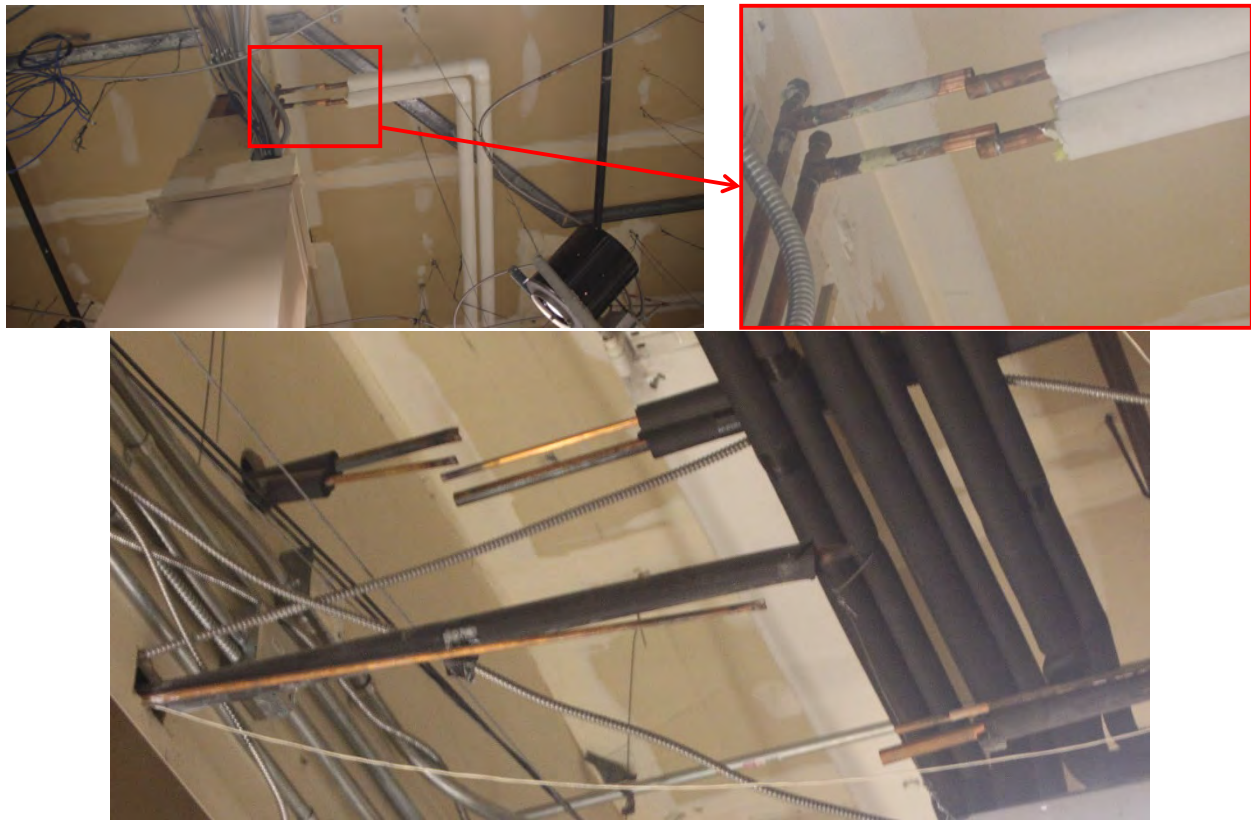


Figure 5.8. Eleven thousand-gallon water tanks at an Eagle River senior-citizen facility slid, shearing off pipe connections and restraining angle bolts, causing water leaks (photos: Wael Hassan).



(a)



(b)

Figure 5.9. (a) Damage to pipes in a grocery store ceiling in Eagle River (photos: Chris Motter). (b) Glycol and water piping without lateral bracing in two Anchorage schools (photos: Reid Middleton (ASD)).

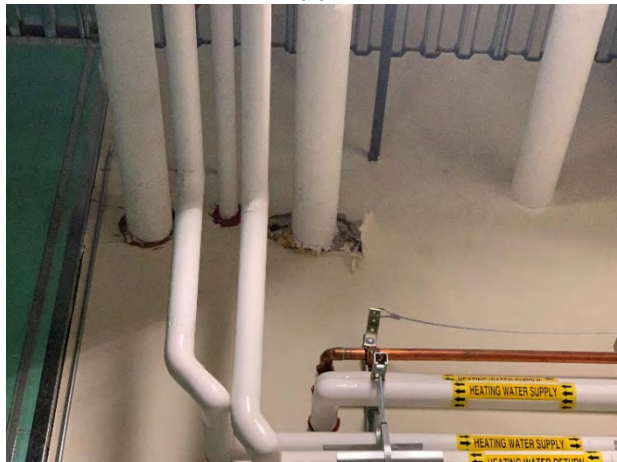
The third source of water/glycol damage was the mechanical-room piping failure of rigid glycol pipes/connections/pumps in the heater system, especially by collision with orthogonal systems and at their connections with poorly restrained mechanical equipment, such as pumps/heater/heat exchangers and other heavy equipment (Figures 5.7, 5.10, and 5.11). Glycol leaks resulted in major damage in many buildings, including schools, hotels, and hospitals. Gruening Middle School in Eagle River, the British Petroleum (BP) Building, and Blood Bank of Alaska (BBA) are quoted examples of such glycol damage. More details on the impact of water and glycol flooding on schools and hospitals can be found in subsequent chapters.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.10. (a) Failed water pipe at an Anchorage hospital, pipe impact with surrounding walls causing damage to both (b) pipes and (c) walls, (d) water damage of electrical wiring and equipment at an Anchorage hospital (photos: Wael Hassan), (e) broken pipe connection to unbraced hot water generator at Bear Valley Elementary (photo: ASD), and (f) rigid-water-pipe connection failures in a mechanical room (photo: Wael Hassan).



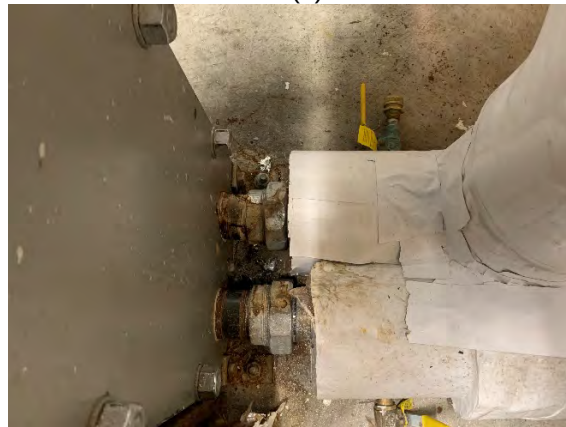
(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.11. (a) Fire-hydrant connection failure (photo: Randy Williams); (b) an Extrol tank surviving the shaking, despite poor tie down restraint, (c) heat-exchanger connection failure and (d) glycol leak, and (e, f) water boiler connection failure (photos: Wael Hassan).

One factor that exacerbated the impact of water damage was the inability of many building owners/operators to shut down water mains in a timely fashion because of unawareness of the location or process of water shutdown or the long waiting time until a professional staff member could arrive to shut down water⁶. In some cases, the water valves had locks to prevent manual shutdown. A clear example of this was the University of Alaska, Eagle River, campus that suffered severe water damage due to many hours of water leakage while waiting for the building staff to arrive.

5.3 Equipment Damage

The most common mechanical-equipment damage observed was sliding of unrestrained (or poorly restrained) heavy equipment, causing damage to connected pipes and ducts and other systems (Figures 5.7, 5.11, 5.12 and 5.16). In some cases, the equipment itself was damaged because of collision with structural or other building systems (Figure 5.13). Some strapped/anchored equipment also suffered damage because of the pull-out failure of a strap or anchor from the wall or floor, which was caused by poor anchorage. It seems that flexible strapping worked better than rigid anchors in equipment restraints; however, the movement associated with flexible strapping is significantly higher than that associated with rigid strapping, and piping should be flexible enough to accommodate this movement. Inertia bases and vibration isolators were poorly bolted (or unanchored) to floors and suffered anchor damage² (Figures 5.14 and 5.15). Roof chillers² and other mechanical equipment were poorly restrained and suffered anchorage failures and sliding (Figure 5.16, 5.17 and 5.18). There were some cases of pump damage (Figures 5.7 and 5.11), but in most cases, the damage was in pipe connections to pumps. Counterweight dislocation and damage in elevators was very common during the earthquake. Many hospital and office buildings suffered reduced operations for hours to days following the earthquake until elevators were repaired.



Figure 5.12. (a) Mechanical equipment damage, (b), (c) Mechanical unit sliding for a few inches: fourth floor of a hospital building, Anchorage (photos: (a) Greg Latreille; (b), (c) Wael Hassan).



(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.13. (a, b) Improperly restrained mechanical-equipment failure; (c–f) mechanical-component failure: duct flanges, VAV box, and VAV ducts (photos: Randall Williams²).



Figure 5.14. Broken nonseismic vibration isolator, Bartlett High School (photo: ASD).



Figure 5.15. Isolator and snubber failures due to improper and undersized anchorage (photos: Randall Williams²).



Figure 5.16. Mechanical-equipment sliding and anchorage failure on roof (photos: Randall Williams²).



(a)



(b)



(c)



(d)



(e)

Figure 5.17. Mechanical-component duct failure: (a, b) University of Alaska, Eagle River, campus; (c, d) Eagle River commercial building; and (e) duct failure at UAA administrative building (photos: Wael Hassan, UAA).



(a)



(b)



(c)



(d)



(e)

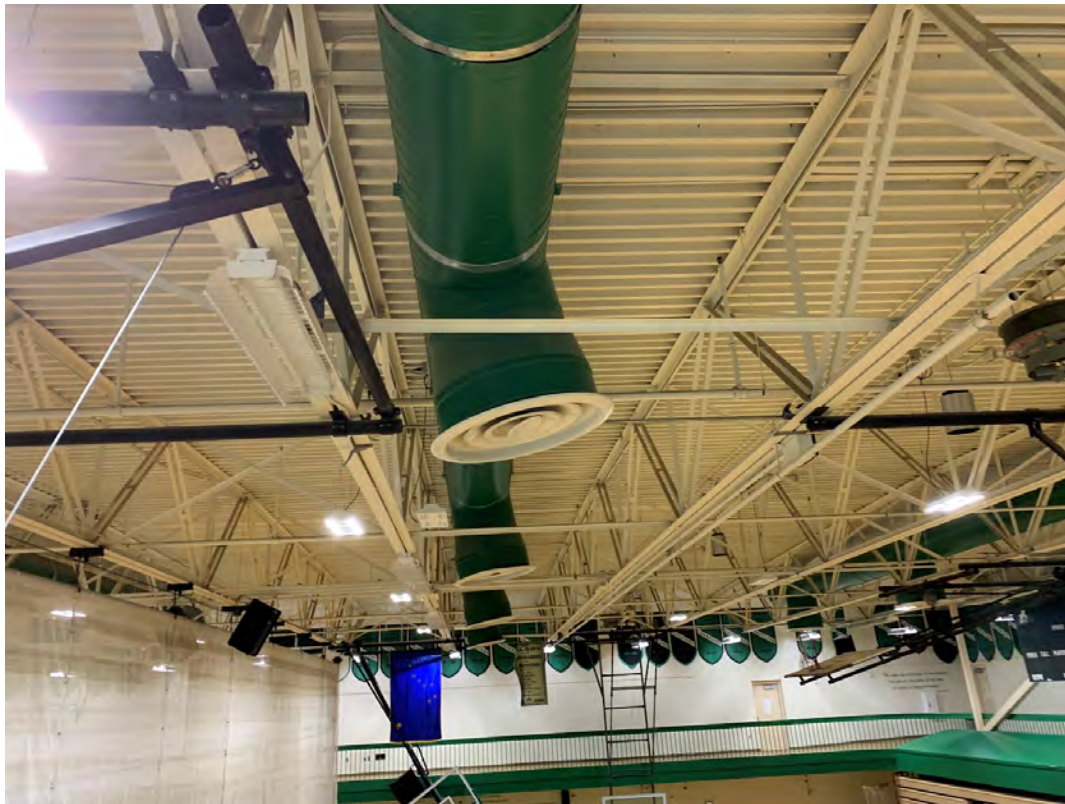


(f)

Figure 5.18. (a) HVAC duct damage to wall and (b, c) duct separation (photos: Randall Williams), (d) duct separation (photo: Wael Hassan), (e) equipment support bending, and (f) connector pipe bending (photos: Randall Williams²).

HVAC systems suffered extensive damage during the earthquake in many older/non-engineered buildings with poor seismic restraints. The main damage was at HVAC ducts (Figures 5.13, 5.17, and 5.18), where duct detachment/separation occurred. Failure of duct straps and collision of ducts with other systems was also observed (Figure 5.19). In some cases, whole segments of ducts fell off the ceiling (Figures 5.13 and 5.17). Some building operators (such as BBA's) reported reduced heating-system efficiency upon restart, following the quick initial repairs, and attributed that to out-of-balance internal mechanical parts of chillers and other compressors. However, although this might be one contributing factor, another factor might be air-duct leakage due to unobserved cracks at connections. Full

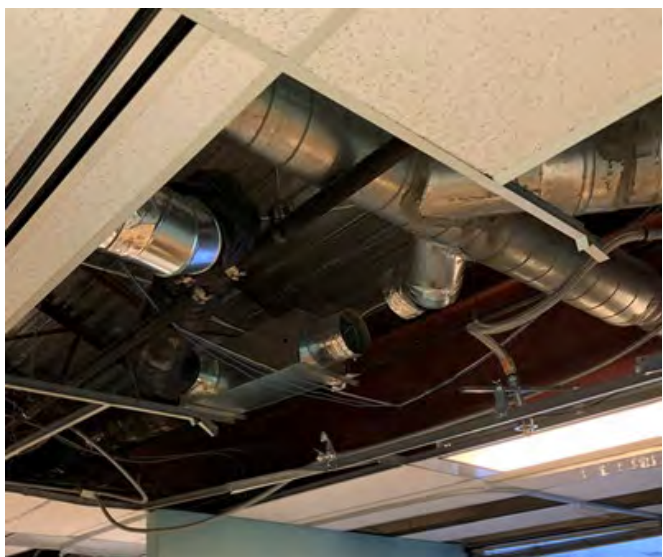
compression tests should be performed following any repairs in HVAC systems or upon reporting reduced heating efficiency following the earthquake. Duct-flange damage and variable-air-volume (VAV) box and duct damage were common during the earthquake² (Figure 5.13). In some cases, permanent residual displacement and major rotation occurred at HVAC ducts (Figure 5.19). New seismic gas valves were efficient, shutting off gas during the earthquake and preventing building damage⁶.



(a)



(b)



(c)

Figure 5.19. (a) HVAC duct rotation and residual deformation, Colony High School, Mat-Su (top photo: Wael Hassan); (b) seismic-strap failure of HVAC duct (photo: Randall Williams²); and (c) air-duct failure in a UAA building in Eagle River (photo: Wael Hassan).

Pieces of heavy electrical equipment, such as data and telecommunication towers, were not restrained to floors or strapped to adjacent walls. As a result, they slid or overturned, causing equipment malfunctioning² and nonstructural damage to walls. Electrical poles in office buildings suffered permanent deformation. Some electrical-panel housings were damaged and detached (Figure 5.20). In one case, the team observed an electrical panel that suffered short-circuit damage due to water leakage, which triggered the fire alarm (Figure 5.20).



(a)



(b)



(c)



(d)

Figure 5.20. (a) Electrical panel short-circuit failure due to water leaks from mechanical room above (photo: Wael Hassan), (b) unrestrained telecom/data tower toppled (photo: Randall Williams), (c) electrical-panel housing detachment and failure, and (d) power-connection failures (photos: Randall Williams²).

5.4 Veneer and Façade Damage

Extensive damage was observed to veneers and façades in Eagle River, and minor-to-moderate damage was observed in Mat-Su and Anchorage. Most of the veneer damage was concentrated in low-rise commercial and office buildings. Examples of damage to clay-brick masonry veneers are shown in Figure 5.21. The extent of damage varied, as evident in the figure. In some instances, damage concentrated at perpendicular corners, while in other instances, damage occurred along an open face.



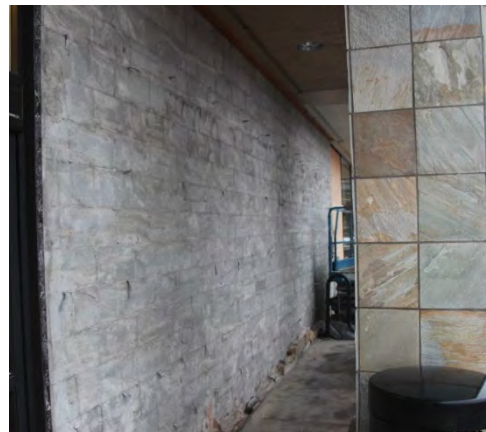
(a)



(b)



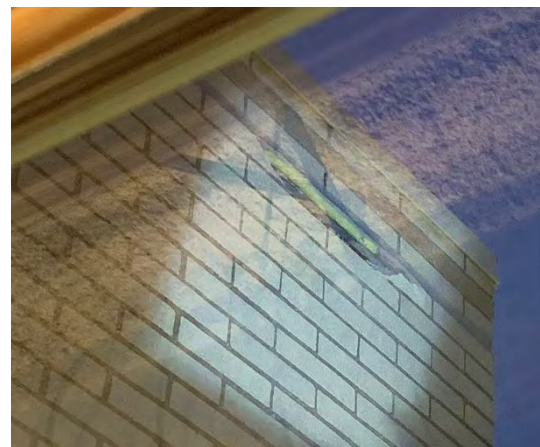
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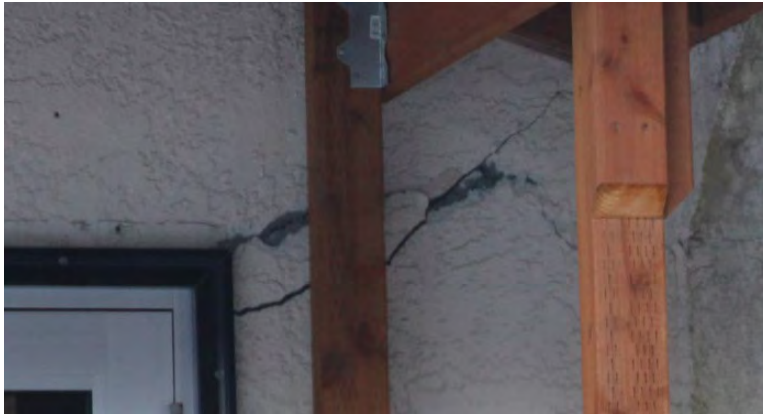
(f)

Figure 5.21. Damage to clay-brick-masonry veneer in buildings in Eagle River and Anchorage: (a,c) business damage, (b) residential damage, (photos a,c Chris Motter; b: ADN), (d, e) Eagle River Library (photo: Walker and Murren³), and (f) An Anchorage hospital building (photo: Wael Hassan).

Examples of damage to concrete façades are shown in Figure 5.22. Damage at corners of openings and corners of perpendicular walls, as shown in the figure, was common. Examples of damage to stone façades are shown in Figure 5.23. Damage to concrete and gypsum façades was less common in Anchorage. Damage to architectural façade elements occurred in several buildings in Eagle River and Anchorage (Figure 5.24).



(a)



(b)



(d)



(c)

Figure 5.22. Damage to concrete and brittle façades at exterior of buildings in Eagle River (photos: (a–c) Chris Motter and (d) Walker and Murren³).



(a)



(b)



(c)



(d)

Figure 5.23. Damage to stone façades at exterior of retail and supermarket buildings in (a) Eagle River and (b) South Anchorage (photos: Chris Motter) and (c) at a supermarket in Eagle River (photo: Wael Hassan). (d) Exterior metal façade school damage (photo: Reid Middleton, ASD).



Figure 5.24. Damage in architectural columns at an Eagle River business building (photos: Wael Hassan).

Damage to windows was extensive in Eagle River, and it was moderate in Anchorage (Figures 5.23, 5.25, and 5.26). One example of significant window damage occurred at the McDonald's, shown in Figure 5.25, which was red-tagged and closed. The building was later demolished. In some cases, window-opening equipment was also damaged (Figure 5.26). Business owners started repairing shattered glass windows soon after the main event; however, in many cases in which special, large glass panels with high thickness and wind resistance is used, such as in large commercial buildings and hospitals, it took several weeks to 2 months until new glass was installed, as it is manufactured and imported from other states. Estimated drift ratios at some mid-rise instrumented buildings exceeded the American Society of Civil Engineers 7-16 drift limit for glass shattering; however, rare incidents of glass shattering problems were found in mid-rise and high-rise buildings in Anchorage.



(a)



(b)



(c)



(d)



(e)

Figure 5.25. (a, b) Window damage at a red-tagged McDonald's (later demolished), (c) at a bank in Eagle River (photos: Chris Motter), (d) at a spread mall in Eagle River (photo: Wael Hassan), and (e) at a retail building in Eagle River (photo: Chris Motter).



Figure 5.26. Damage to windows at retail and commercial buildings in Eagle River and a hospital in Anchorage (bottom right) (photos: Wael Hassan).

5.5 Ceiling Damage

Damage to suspended grid ceilings was extensive in many buildings in Eagle River, Anchorage, and Mat-Su, including supermarkets and department stores, hospitals, schools, retail buildings, and commercial buildings. From reconnaissance observations, it appears that mid-rise and high-rise buildings built after the mid-1980s had the least direct ceiling damage (i.e., not resulting from water flooding). Direct suspended-grid ceiling damage was more pronounced in low-rise buildings (one to two stories). Grid ceiling damage was significantly more pronounced in low-rise buildings in Eagle River compared to the Anchorage Bowl, sometimes, ironically, in structures with very comparable type and geometry.

One example (Figure 5.27) is shown for a retail store. The damage typically consisted of falling tiles, with damage to the metal grid and the lighting occurring in some instances. The most extensive damage to ceilings was observed in Eagle River and Mat-Su, and specific examples of buildings with significant ceiling damage are discussed in this section.

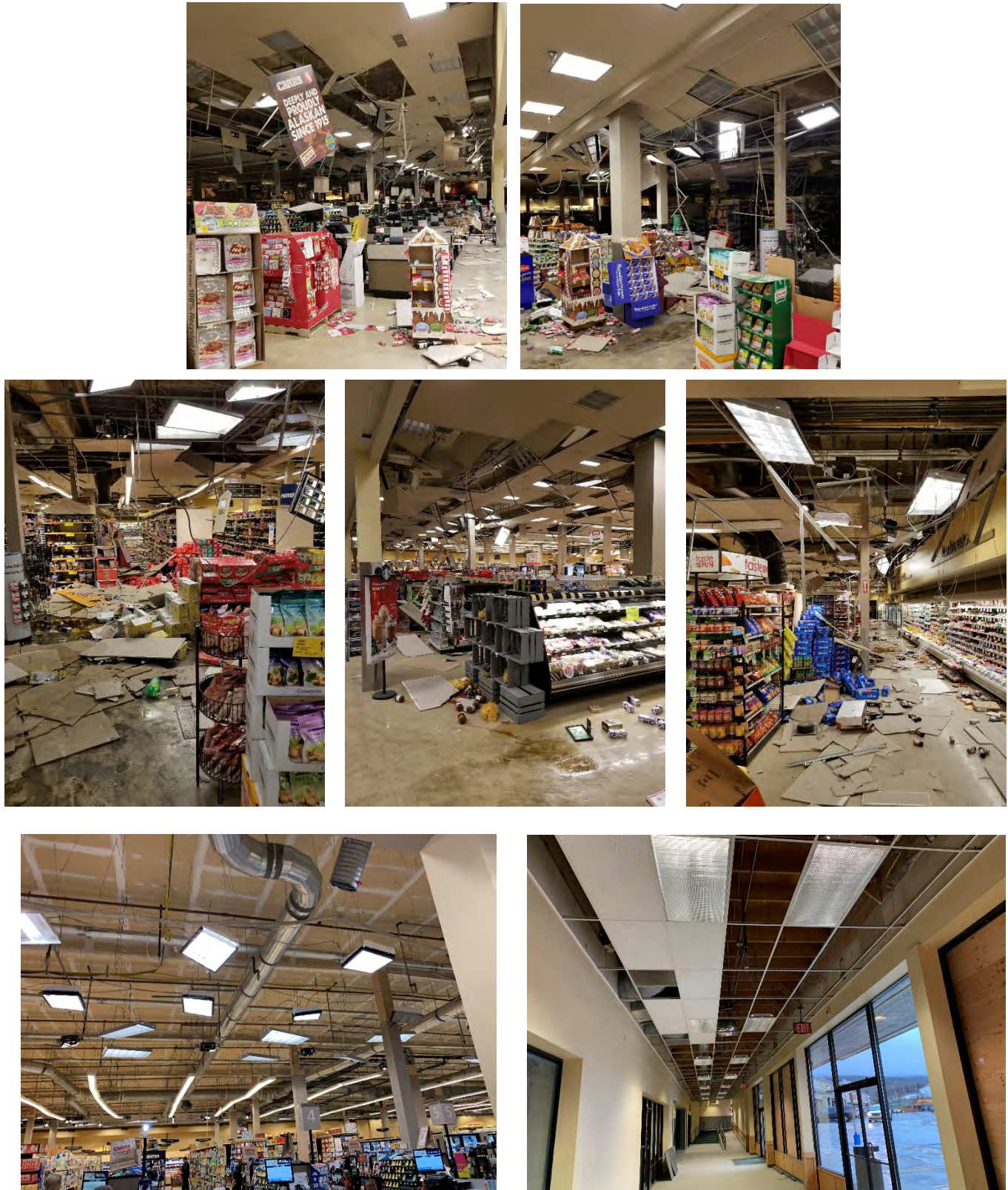


Figure 5.27. Heavy ceiling damage in Eagle River commercial buildings leading to complete ceiling removal (photos: Carr's, Wael Hassan).

Extensive damage to suspended ceilings was observed at Carr's (Albertson) Supermarket in Eagle River, as shown in Figure 5.27. Much of the information provided in this paragraph was based on accounts of the damage and aftermath provided by a store manager and employees. Following the earthquake, a structural inspection was conducted, but no significant structural damage was reported. The observed damage was primarily nonstructural. Severe damage to suspended ceilings was observed, and this included localized failed grid ceilings, tiles falling, and the residual downward deformation of the suspended ceiling grid. Pipe connections of various sizes failed, leading to misalignment of pipe segments following the earthquake. Damage to the storefront was also observed, and this included glass and the façade. Minor cracking in one column was observed. According to multiple store employees, the earthquake felt like an impulse followed by shaking. No employees were reported to be injured in the earthquake. Flooding occurred; however, the main financial losses were attributed to loss of refrigeration and spoilage of product. The store was reopened on Saturday, December 8, 2019. The drop-ceiling grid was not replaced in order to leave an open ceiling. In comparison, the nearby Fred Meyer supermarket in Eagle River did not have a suspended ceiling and had minimal damage. In comparison to another Carr's (Albertson) Supermarket built in 1982 in South Anchorage, close to the maximum recorded peak ground acceleration (PGA) of 0.55g, the store has the same footprint and structural system of its Eagle River counterpart, but other than glass façade damage and a few ceiling-tile falls, minimum damage was observed (Figure 5.28).



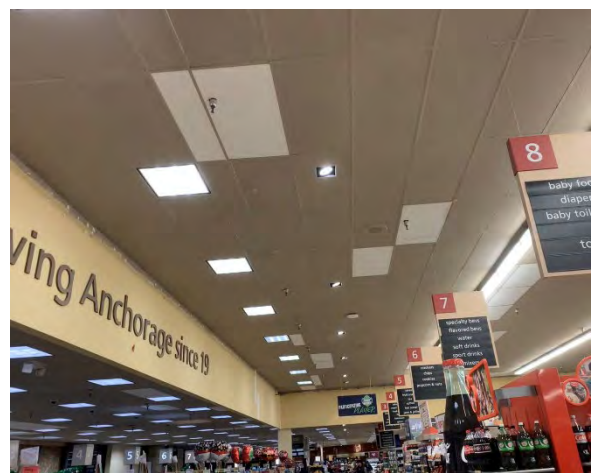
(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.28. Ceiling damage: (a) office building (photo: Randall Williams²), (b) coffee shop in Eagle River (photo: Wael Hassan), (c–e) supermarket in South Anchorage (photos: Wael Hassan), and (f) grocery store in South Anchorage (photo: Chris Motter).

Extensive ceiling damage due to water and glycol flooding was observed in many school, hospital, and office buildings in Anchorage, Eagle River, and Mat-Su. One example is shown in Figure 5.29, where the first-floor ceiling of the BBA in Anchorage was severely damaged because of water and glycol flooding from the penthouse-mechanical-room connection failures. Another example is shown in Figure 5.30. The reader is referred to Chapters 6 and 7 of this report for more details about hospital and school damage. Repairing the impact of water flooding and replacing ceiling tiles (and grids sometimes) was the most time-consuming and costly repair item in many buildings, delaying restoration of full operation of the building to many weeks following the main event.



Figure 5.29. Ceiling damage at the BBA (photos: BBA).



(a)



(b)

Figure 5.30 Ceiling damage in (a) a Mat-Su Valley Colony High School and (b) an Anchorage hospital (photos: Wael Hassan).

At the UAA building in Eagle River, extensive damage to suspended grid ceilings was also observed, as shown in Figure 5.31. Ceiling damage was a combination of grid failure due to intense shaking, substandard grid hangers that failed extensively, and water flooding. The building was a steel-frame structure with large beams and columns. Residual deformation of moment frames, indicative of plastic hinging, was not visually detected. The ceiling damage included falling

ceiling panels, damage to the metal grid, water damage, and damage to ductwork above the suspended grid ceiling. The HSB at UAA, a 2015 steel-braced-frame building, received a free-field PGA of 0.21g; however, the shaking was intense because of the higher stiffness of the building, causing damage to ceiling tiles and grids, particularly to heavy, wooden-tile ceilings, and firefighting-system failure that led to water flooding of some ceiling areas (Figure 5.32).

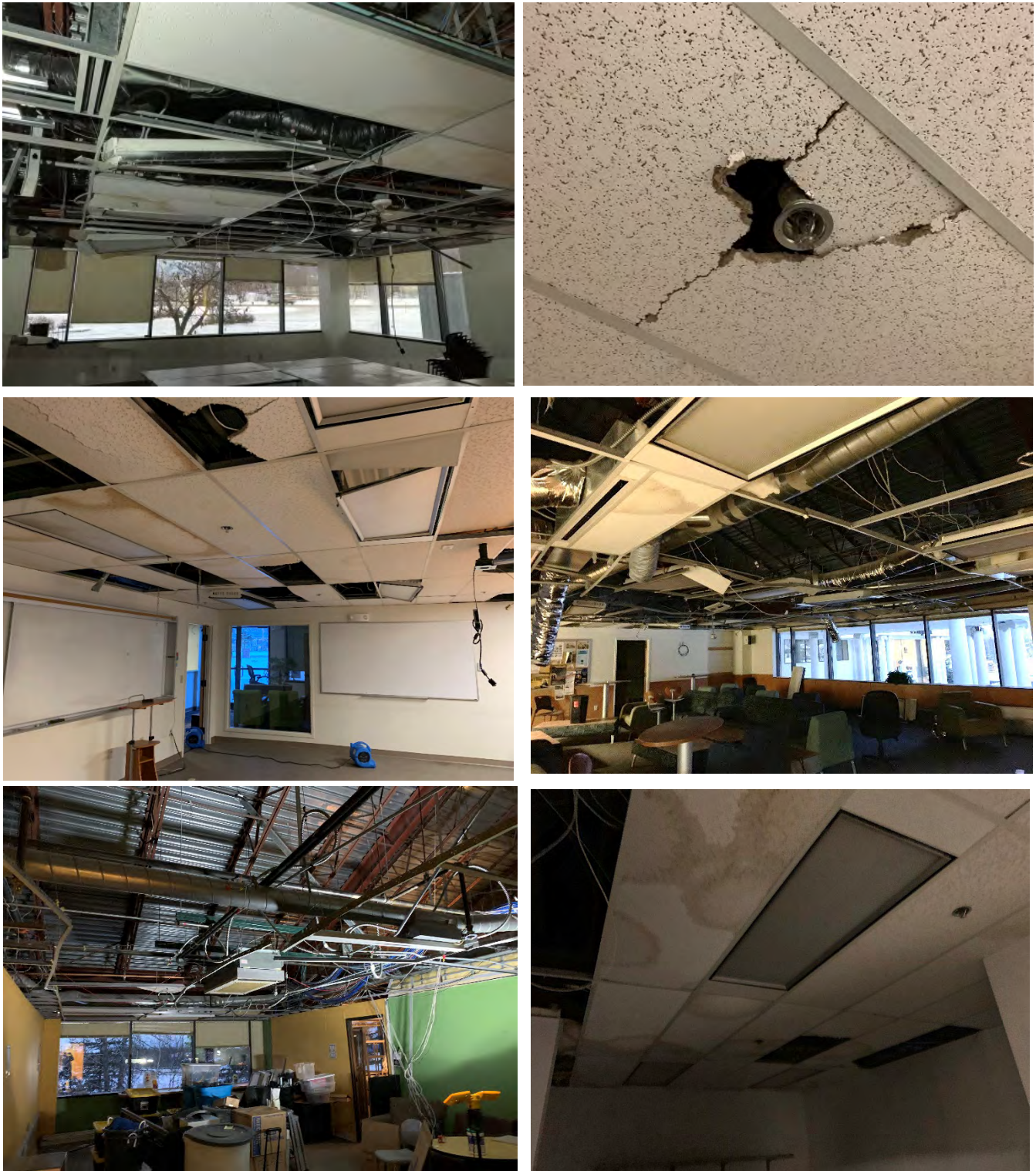


Figure 5.31. Eagle River campus of UAA with various degrees of ceiling damage; the second-floor ceiling suffered extensive damage from shaking and poor bracing, while the first-floor ceiling damage was more related to water flooding from sprinkler system failure (photos: Wael Hassan).



Figure 5.32. The 2015 UAA HSB (PGA 0.21g) ceiling damage. Large, heavy wooden ceiling tiles fell, and the grid failed because of wire snapping; however, in the same building, the acoustic light tiles and grid had minimum damage (photos: Wael Hassan).

Although nonstructural damage in South Anchorage was not as widespread as in Eagle River and Mat-Su, there were some observations of damage to suspended grid ceilings in department stores in South Anchorage, with one example shown in Figure 5.33. Damage to ducts was evident at many schools and at the UAA building in Eagle River.



Figure 5.33. Damage to a suspended grid ceiling at Finger Lake Elementary School in Mat-Su (photo: Chris Motter).

Damage to suspended grid ceilings was also observed at schools. Examples are shown for Eagle River in Figure 5.34 and Mat-Su in Figure 5.35. It is worth noting that falling ceiling tiles can pose substantial life safety hazards in some cases, such as the case of a Mat-Su school basketball court (Figure 5.35), where heavy wooden ceiling tiles (weighing 30 lb each) fell off a height of 40 feet onto the court, fortunately not injuring or killing any student, as it was still early in the morning. In addition to damage to suspended grid ceilings, damage to ceiling tiles was also observed. One example was the gymnasium at Eagle River Elementary School, shown in Figure 5.36, where many ceiling tiles had fallen during the earthquake.



(a)



(b)

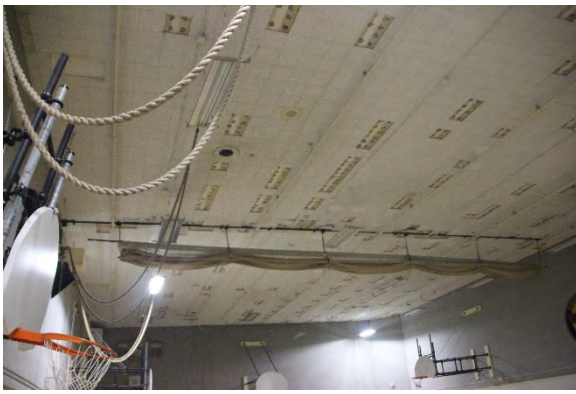


(c)



(d)

Figure 5.34. Damage to suspended grid ceilings in (a–c) Eagle River Elementary School and (d) a grocery store in Anchorage (photos: Chris Motter).



(a)



(b)

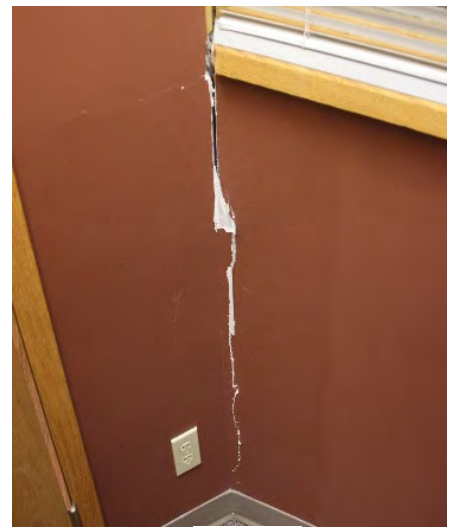


(c)

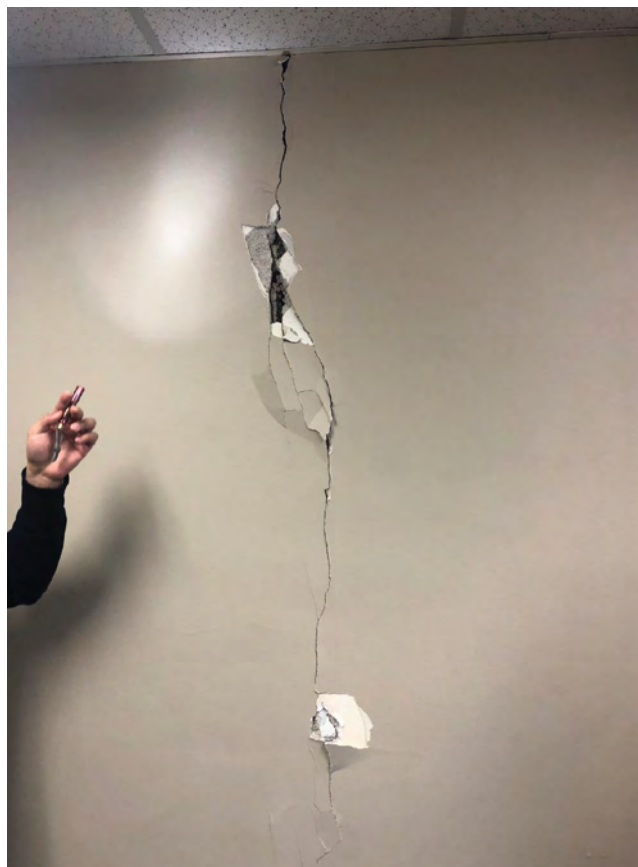
Figure 5.35. Damage to ceiling tiles in a (a, b) gymnasium and (c) classroom of Eagle River Elementary School (photos: Chris Motter).



(a)



(b)



(c)

Figure 5.36. (a, b) Damage to nonstructural walls at an office building in Anchorage (photo: Chris Motter) and (c) partition-wall cracks at a concrete-core-wall interface in an office building in Anchorage (photo: Patrick Murren³).

Falling ceiling tiles can pose a life safety hazard during earthquakes. It is clearly evident from the observed damage that suspended grid ceilings did not perform well during this earthquake in a large number of low-rise buildings in the Northern Communities, in Mat-Su, and, to lesser extent, in Anchorage. The damage was especially more remarkable in stiff and older buildings constructed prior to 1985 in Anchorage, in contrast to newer and more flexible buildings. Fortunately, no loss of life occurred as a result of falling ceiling tiles. It is recommended that suspended-ceiling systems with movement joints be used in place of standard grid ceilings to mitigate the life safety risk posed by falling ceiling tiles. Some

gymnasiums, schools, and stores in the region made a decision to abandon the use of suspended ceilings altogether and rely on exposed ceilings as a result of this earthquake.

5.6 Partition and Nonstructural Wall Damage

Extensive damage was observed to nonstructural partition walls as a result of the earthquake. Damage to partition walls was observed in various types of buildings, as evident in Figures 5.36, 5.37, 5.38, 5.39, and 5.40. Typical cracking observed in nonstructural partition walls included cracks initiating at openings (e.g., created by windows or doors) and cracks occurring at interfaces of nonparallel walls. In some instances, diagonal cracking was observed. A few buildings with particularly severe damage to nonstructural partition walls are discussed in more detail in this section.



Figure 5.37. Wall damage in a house in Mat-Su near Finger Lake (photos: Chris Motter).

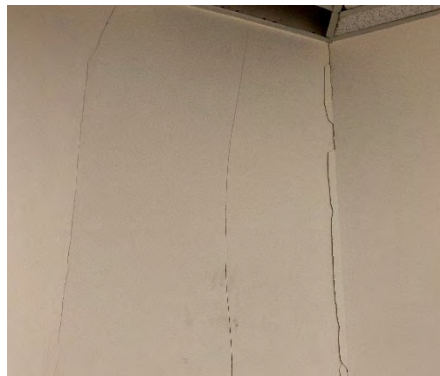


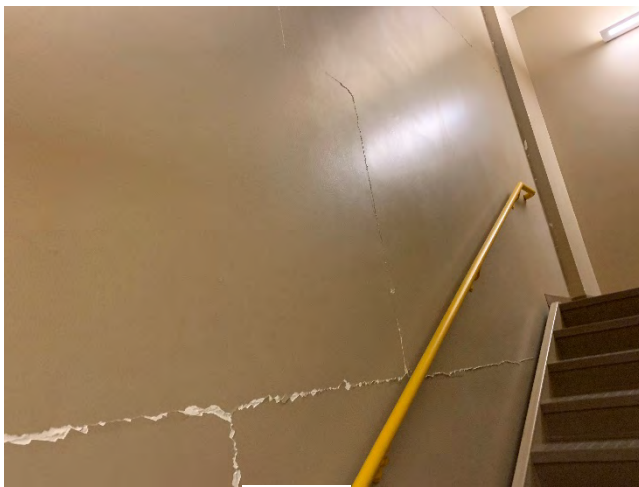
Figure 5.38. University of Alaska, Eagle River campus, partition and nonstructural wall damage. The top left photo shows an unstable partition wall with out-of-plane deformation. The building is flexible steel-moment frame, and the nonstructural wall components were not compatible with withstanding the large frame deformations (photos: Wael Hassan).



(a)



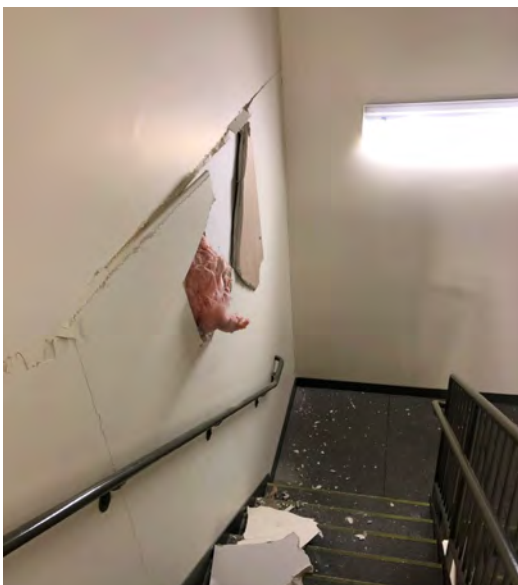
(b)



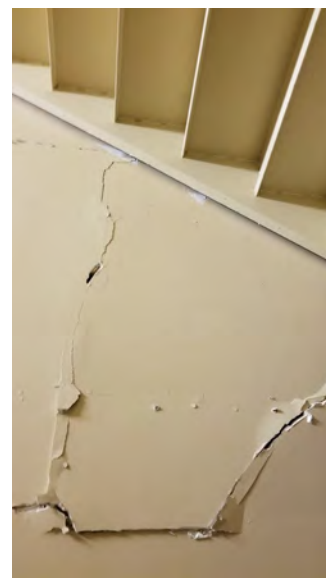
(c)



(d)



(e)



(f)

Figure 5.39. Typical stairwell sheetrock damage in office buildings and hospitals in Anchorage (photos: (a–d) Wael Hassan, (e) Randall Williams², and (f) Greg Latrielle⁷)



Figure 5.40 Typical partition-wall sheetrock damage in office, hospitality, religious, and educational buildings in Anchorage and Eagle River (photos: Wael Hassan).



(a)



(b)



(c)



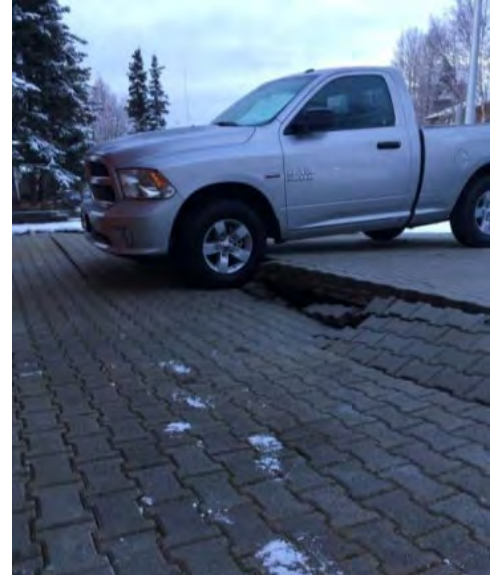
(d)



(e)



(f)



(g)

Figure 5.41. Sample floor damage due to soil failure; (a) residential wood building (photo: MOA); (c) 2014 multistory building in Eagle River (photo: Wael Hassan); (d) An Anchorage hospital (photo: Wael Hassan); (e) school building (photo: Reid Middleton, ASD); (f) Gym damage following control joint (photo: Reid Middleton, ASD); (g) residence driveway (photo: MOA).

Significant damage to nonstructural partition walls was observed in a house in Mat-Su, as shown in Figure 5.37. The house had structural damage in addition to nonstructural damage, with more details provided in Chapter 4. Given the significant level of damage observed at the house, it is conceivable that the house may have experienced ground motions that were higher than those in other nearby areas. The house was located at the edge of a lake, which may have led to local amplification of the ground motion at this site. The damage at this house included diagonal cracking in partition-wall panels, indicative of failure in shear. Cracking at the corners of windows, doorways, and stairs was also observed in a number of nonstructural walls. Additionally, cracking at the interface of perpendicular walls was prevalent. In many cases, the panels were damaged to the point that replacement was necessary.

At the UAA Eagle River building, extensive damage to partition walls was observed, as shown in Figure 5.38. Residual deformation was evident in some partition walls, while others had failed connections such that the walls were no longer attached. Flooding had occurred in the building as well, which led to damage at the base of all partition walls, as shown in Figure 5.38. The building has a flexible steel-moment frame, and the nonstructural wall components were not compatible with withstanding the large frame deformations.

Typical partition-wall and stairwell-wall sheetrock damage patterns in Anchorage and Eagle River office buildings are depicted in Figures 5.36, 5.39, and 5.40. Damage ranged from cosmetic to extensive. Even in those buildings receiving less than 0.2g PGA, sheetrock damage was widespread. Aftershocks have exacerbated the sheetrock damage problems in the region. The cost of repair of this type of crack can be relatively high, especially with stairwells needing scaffolding. This cost constituted a significant portion of the total earthquake damage repair cost at many facilities in Anchorage and Eagle River. Some preexisting sheetrock cracks were the result of previous earthquakes in the past few years that have not been repaired. Similarly, some facility owners decided to defer fixing the sheetrock cracks to future building improvement projects. Since it was widespread damage, FEMA has denied earthquake assistance to some facilities that had only this type of damage. The local practicing engineering community is discussing the need for more ductile wall-finishing material in seismically active Southcentral Alaska.

Floor concrete and finished cracking and damage due to soil failures was widespread in all types of buildings. Residential single family houses garages and driveways were the most affected, (Figure 5.41).

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6 PERFORMANCE OF SCHOOLS

6.1 Overview: School Background in Southcentral Alaska

The earthquake-affected area includes Alaska's two largest school districts by student population: the Anchorage School District (ASD) with nearly 46,000 students (ASD, 2019a),¹ and the Matanuska-Susitna (Mat-Su) Borough School District (MSBSD) with over 19,000 students (MSBSD, 2019a).² ASD covers nearly 2,000 square miles, while MSBSD covers more than 25,000 square miles (ProximityOne, 2019)³ and is the sixth-largest district in the nation in geographic area. These districts experienced the vast majority of the school damage during the earthquake. Shaking was also felt across the Kenai Peninsula Borough School District (KPBSD) further south, but impacts were minor. Several KPBSD schools experienced minor nonstructural damage to ceilings, water pipes, and heating systems, which led to early release of students on the day of the earthquake, but all schools reopened on Monday, December 3 (Petersen, 2018).⁴ Several schools in Homer and Seward evacuated because of the tsunami warning (Bolton and Gross, 2018).⁵ The remainder of this chapter discusses impacts to Anchorage and Mat-Su schools.

At the time of the earthquake, ASD had 86 school buildings, with 97 schools or programs in them: 59 elementary schools, 11 middle schools, 13 high schools, 1 K–12 school, and 13 charter schools or schools with special missions. MSBSD had 47 schools: 21 elementary schools, 5 middle schools, 8 high schools, 4 K–12 schools, and 9 charter schools or schools with special missions.

A few schools in both districts predate the 1964 earthquake, but most schools were built afterward. MSBSD has school facilities with a range of building dates from the 1950s to the 2010s, although the majority of schools were built in the 1970s, 1980s, and after 2000 (MSBSD, 2019b).⁶ Structural systems are primarily wood-frame, reinforced concrete-masonry-unit (CMU) masonry, steel-braced frame, steel-moment frame, and reinforced-concrete shear wall systems; MSBSD has no unreinforced masonry buildings (MSBSD, 2019b). Anchorage schools are a bit older, with 24 facilities over 50 years old.

Depending on their age, ASD and MSBSD schools were designed to the editions of either the *Uniform Building Code (UBC)* or *International Building Code* adopted by the municipality of Anchorage (MOA) and the Mat-Su Borough, respectively, at the time of design. Schools under construction have daily site inspections from ASD's Capital Planning and Construction Department, as well as MOA inspections at key points during construction, even for those sites outside the Building Safety Service Area. Mat-Su schools are inspected during construction by the Facilities Department and, for major projects such as new school construction, by Mat-Su Borough Capital Projects staff. The borough owns MSBSD school facilities.

6.2 Earthquake Shaking and Geotechnical Impacts on Schools

Because of the size and varied geology of both districts, shaking at schools varied significantly, especially across the Mat-Su district. Available data discussed in Chapter 2 indicate that most ASD schools experienced peak ground accelerations (PGAs) of at least 0.2g. Five of Anchorage's 25 strong-motion stations are located at schools; PGA values at the schools ranged from 0.12g to 0.24g. PGAs of 0.23g at the Houston City Hall (AHOU) station and of 0.14g at the Alaska Tsunami Warning Center (K218) station were recorded approximately 5 km from the most significantly damaged MSBSD schools. The Chugiak Fire Station (K217) station is about 10 km from the two ASD schools with significant structural damage, although topographic and geologic variations in the area mean that motions at the school sites may have been stronger than those measured at K217. The U.S. Geological Survey Science Center (8047) station is located near several schools, including King Tech Vocational High School. Figure 6.1 compares response spectra for these records.

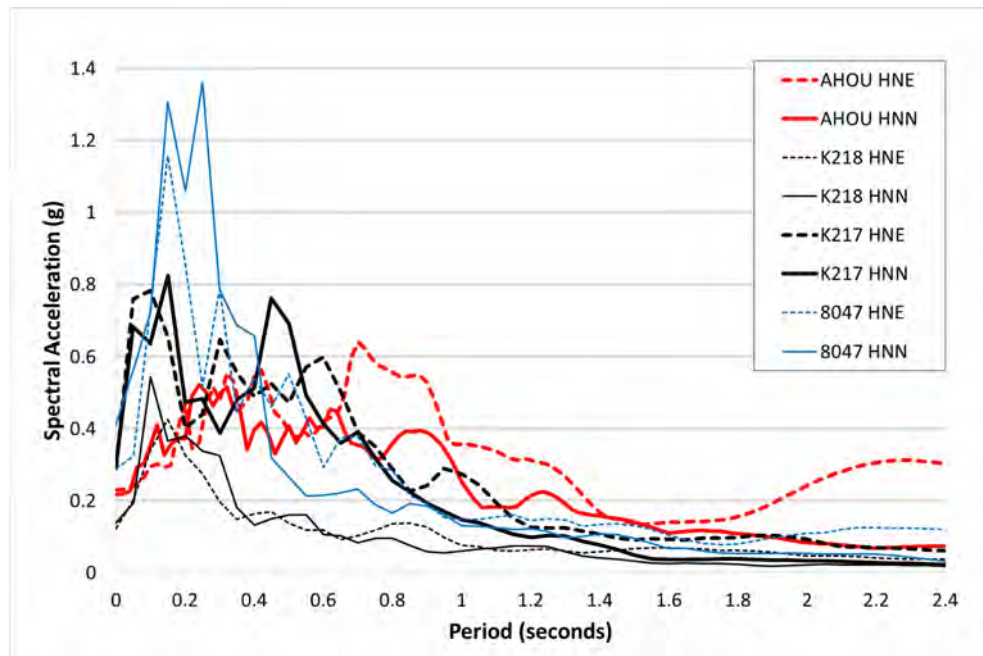


Figure 6.1. Response spectra for selected strong-motion recordings within 5–10 km of damaged schools: AHOU in Houston/Big Lake, K218 west of Palmer, K217 in Chugiak, and 8047 near King Tech High and University of Alaska, Anchorage.

Evidence of ground failure was present at several schools. Observations included ground cracking, sand boils, vertical ground displacements, and a sinkhole related to a water-line break. Many of these observations were in areas without structures, where fill compaction may have been less than is typical for structural areas. No school buildings in either district experienced significant damage due to ground failure, except for a relocatable (i.e., portable) building undermined by the aforementioned sinkhole caused by the water-line break.

6.3 Structural Impacts on Schools

6.3.1 Damage Overview

Across the ASD and MSBSD, 3 school buildings out of 132 suffered structural damage severe enough to render them unsafe and necessitate closing them for the remainder of the school year. Houston Middle School near Big Lake, and Eagle River Elementary and Gruening Middle School in Eagle River were heavily damaged and red-tagged. On the basis of strong-motion recordings at the stations described in the previous section, these three school sites may have experienced PGAs in the $0.2g$ – $0.3g$ range or higher. We describe damage to each school, and its causes, in subsequent sections.

Minor structural damage, such as hairline cracking in the joints of reinforced-CMU walls, was observed at an additional 14 schools in the Mat-Su district. In Anchorage, 15 damaged schools, 7 of which were in the Eagle River/Chugiak area, received special thorough structural assessment/review in addition to the post-earthquake engineering inspections that all schools received. Of these 15, 2 had major structural damage (Eagle River Elementary and Gruening Middle), 5 had moderate damage, and 8 had minor damage.

6.3.2 Schools with Major Structural Damage

6.3.2.1 Houston Middle School

Houston Middle School, a 1986 reinforced-CMU and steel-frame two-story building, suffered by far the most structural damage of Mat-Su schools. The building has three structurally separate portions: a two-story academic/classroom wing on the south side, a single-story administrative wing in the center, and a two-story athletic wing including the gymnasium on the north side. The lateral system consists of partially grouted, CMU shear walls laid in stack bond (rather than the stronger and more typical running bond), with a pitched roof with a flexible wood diaphragm and a concrete floor (on steel deck) at the first floor.

Several steel roof girders in the classroom wing bore directly on tall (up to 20 feet/6 m) CMU corridor walls, without a supporting column beneath. Per a post-earthquake engineering inspection, the bond beams at the top of the CMU walls shown on the drawings, into which the beam connections and other roof member connections were supposed to be made, were not built (Burkhart Croft Architects (BCA) et al., 2019)⁷. Instead, the girder-wall connections were made by embedding shear studs in a grouted cell in the top course of CMUs, resulting in a weaker connection. Several of these connections failed during shaking (Figure 6.2), leaving the girders in danger of unseating in an aftershock and falling into the classrooms below.



Figure 6.2. Failed connection between a steel roof girder and a CMU wall at Houston Middle School: (a) second story of classroom wing (photo: Bill Noyes) and (b) similar failed connection (photo: Janise Rodgers).

Other damage at Houston Middle included significant cracking of the partially grouted stack-bond classroom-wing CMU walls (both shear walls and partitions) and CMU wall cracking in numerous other locations. Cracked vertical joints in the stack-bond masonry were widespread. In some locations, fallen and loose blocks created a significant safety hazard, including in the gymnasium, where differential movement of the steel roof trusses cracked the surrounding CMU (Figure 6.3). Post-earthquake investigations determined that CMUs were installed without reinforcement in some isolated locations at the tops of walls and around structural steel members and that reinforcing was 48 inches on center, twice the spacing that the current code (*TMS 402-16*)⁸ requires for walls with this bond type (BCA et al., 2019). The building also experienced extensive nonstructural damage, including major damage to suspended ceilings, lighting, and ductwork and damage to finishes and other building systems.



Figure 6.3. CMU block at top of wall cracked and loosened because of differential motion of steel roof framing, Houston Middle School. Loose blocks pose a falling hazard to those below (photo: MSBSD).

6.3.2.2 Eagle River Elementary School

Significant damage was observed in the gymnasium of Eagle River Elementary. The CMU masonry walls separated from the mezzanine because of failure of the wood nailer atop the CMU wall in cross-grain tension (BDS Architects, 2019a)⁹. The damage resulted in post-earthquake installation of vertical bracing to support the mezzanine. Additional damage in the gymnasium was observed in the masonry walls. An exterior masonry veneer had partially separated from the structural CMU wall, which had displaced outward by a small amount. The masonry walls of the gymnasium were braced out of plane from the outside of the building, as shown in Figure 6.4. The clay-brick veneer had been removed to anchor the braces directly to the CMU wall. Aside from the damage in the gymnasium, damage to shear walls was observed in other locations in the building. This damage includes shear cracking in masonry walls (diagonal and stepwise), as shown in Figures 6.5, 6.6, 6.7, and 6.8, and vertical cracking at the interface of perpendicularly oriented masonry walls, as shown in Figure 6.7. A member of the maintenance staff who was in the building during aftershocks reported that the walls vibrated severely during aftershocks. Cracking was observed in the concrete floors in the basement of the building, as shown in Figure 6.9.



(a)



(b)

(c)

Figure 6.4. Exterior shoring for gymnasium wall at Eagle River Elementary: (a) loose portion of exterior masonry veneer removed, (b) displacement of exterior veneer, and (c) interior photo showing separation between gymnasium ceiling and wall (photos: (a) Chris Motter and (b, c) ASD).



Figure 6.5. Damage to masonry walls at Eagle River Elementary (photo: Chris Motter).

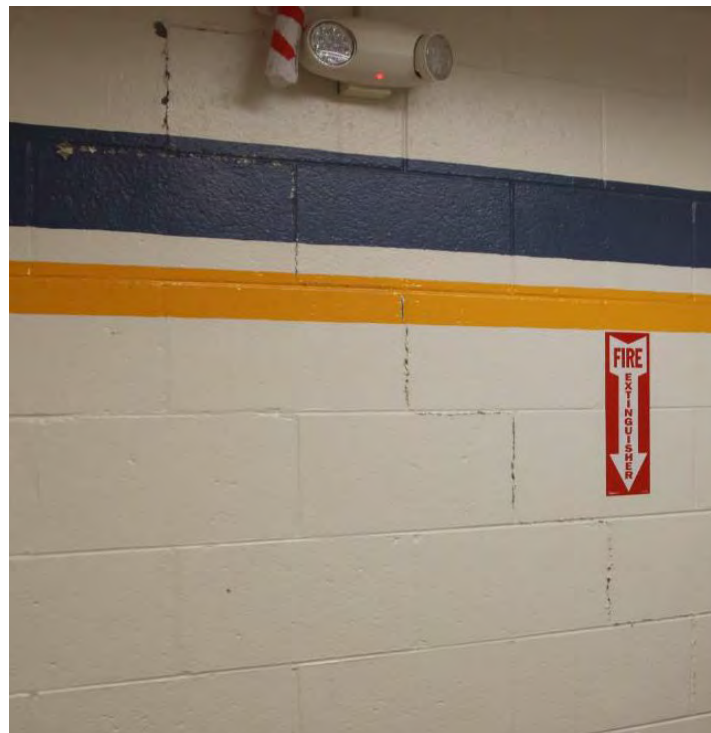


Figure 6.6. Stepwise shear cracking along mortar joints in masonry wall at Eagle River Elementary (photo: Chris Motter).



Figure 6.7. Vertical cracking at interface of perpendicularly oriented masonry walls at Eagle River Elementary (photos: Chris Motter).



Figure 6.8. Cracking at upper corner of masonry wall at Eagle River Elementary; note vertical shoring due to failed roof-wall connections (photo: Chris Motter).



Figure 6.9. Cracking in reinforced concrete basement floor at Eagle River Elementary (photos: Chris Motter).

6.3.2.3 Gruening Middle School

Gruening Middle School was built in 1981 to the 1979 UBC, and has experienced numerous modifications since the discovery was made, near the completion of construction, that the building was not adequately designed or constructed for seismic forces, necessitating the application of corrective measures on the nearly completed structure (BDS Architects, 2019b)¹⁰. The building is made of CMUs (with stack-bond walls) and timber, with some steel members. It has complicated geometry, added seismic measures, and renovations. The building had a Tier 3 *American Society of Civil Engineers (ASCE)* 41 assessment in 2015, and a number of measures were recommended at that time but had not been implemented at the time of the earthquake.

Earthquake damage included a failed top-of-wall connection between CMUs and wood diaphragms at two known locations, causing the CMU walls to separate from floor and lean. Figure 6.10 depicts the damaged CMU wall-floor connections and the braced leaning CMU wall. The earthquake also led to damage to and spalling of CMUs around steel columns and cracking in the stack-bond CMU walls (BDS Architects, 2019a). Other structural damage included permanent residual drift in two steel columns supporting the gymnasium roof (Figure 6.11). Earlier assessments had identified that the CMU walls were inadequately reinforced; plywood shear walls were not connected between floors, continuous, or adequately nailed; and unblocked diaphragm spans were too long, with unreinforced openings, among other deficiencies (BDS Architects, 2019a).



(a)



(b)

Figure 6.10. (a) Separated gymnasium CMU wall from floor joists because of failure of connection at Gruening Middle School with (b) detail (photos: Wael Hassan).



(a)



(b)

Figure 6.11. (a) Separated gymnasium CMU wall from floor out-of-plane supports at Gruening Middle School and (b) wall-floor connection damage and separation from outside (photos: Wael Hassan).

Damage to CMU masonry infill included crushing of masonry and exposure of rebar along the interface between the reinforced masonry infill walls and steel columns, as shown in Figures 6.12 and 6.13. The absence in integrity reinforcement can be observed in between the steel columns and the CMU walls. The steel columns supported long-span steel trusses that spanned across the gymnasium. The observed damaged may have occurred because of incompatibility in deformation between the steel columns and the masonry infill walls and the associated pounding that occurred between the two components.



(a)



(b)



(c)



(d)

Figure 6.12. Spalled CMU around steel columns. (photos: (a, b) Chris Motter and (c, d) Wael Hassan).

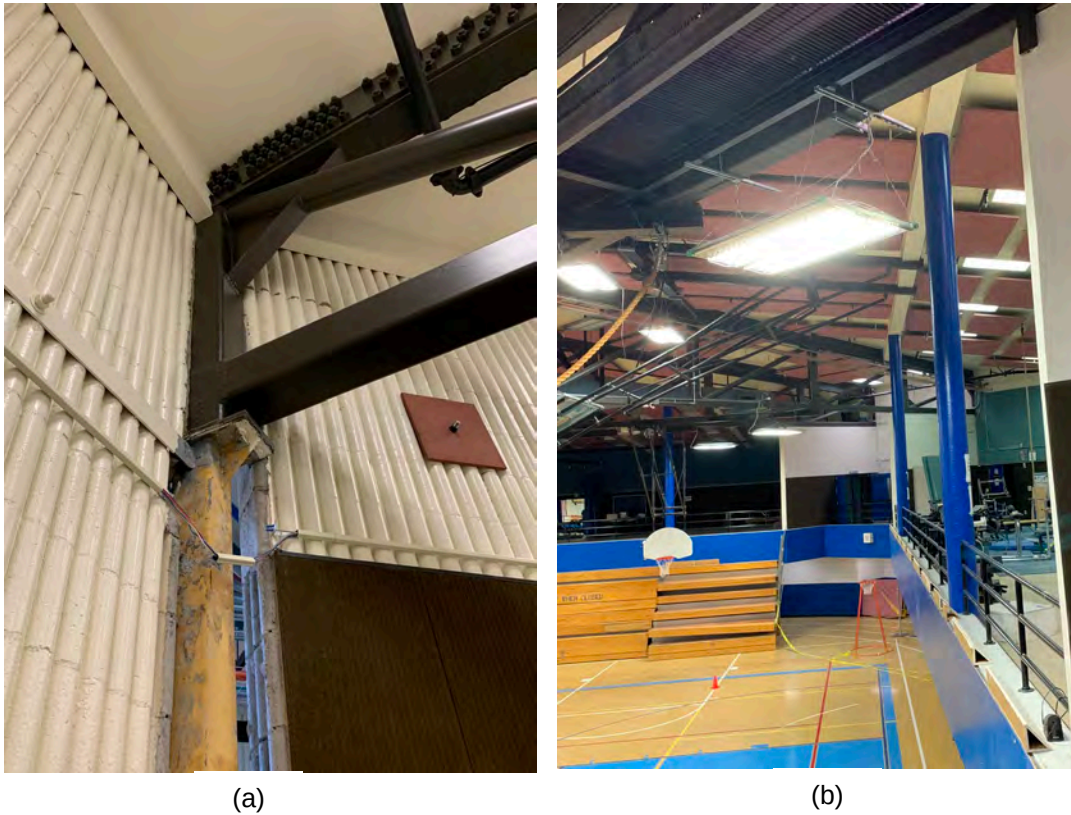


Figure 6.13. (a) Steel column supporting truss separation from CMU wall and (b) permanent drift at Gruening Middle School gymnasium steel columns (Photos: Wael Hassan).

Initially, geotechnical problems were suspected, but geotechnical investigations showed that ground failure was not an issue at the site (engineering team, *pers. comm.*, 2018).

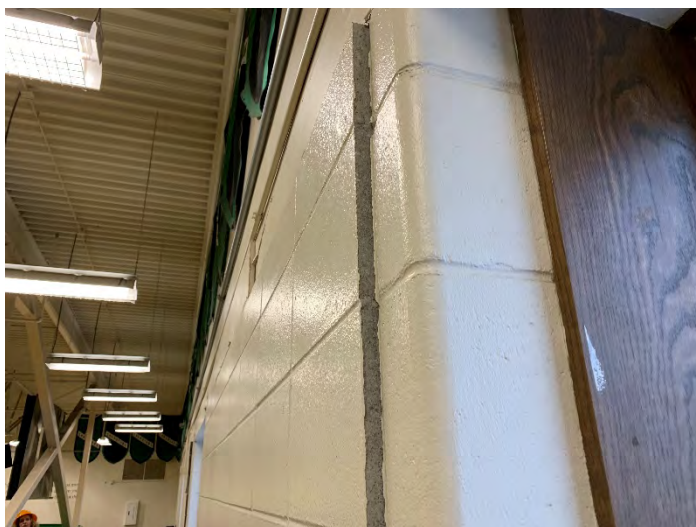
6.3.3 Structural Damage to Other Schools

Fifteen schools in ASD required further thorough structural assessment because of relatively heavier structural damage. Those include the two heavily damaged schools, Gruening Middle and Eagle River Elementary, along with five other schools in Eagle River and eight schools within the Anchorage Bowl.

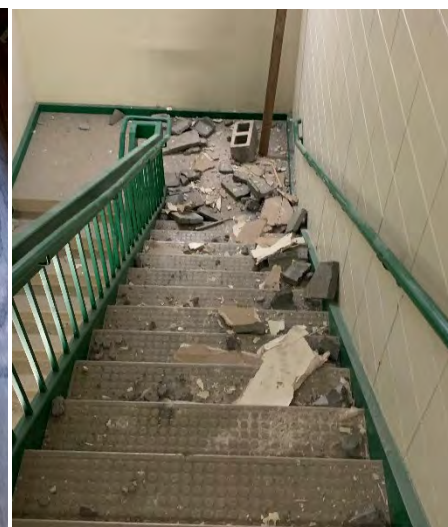
Reinforced CMU walls in the Colony High gymnasium, at the upper running track and in a stairwell, suffered severe cracking and block dislodging (Figure 6.14). The observed damaged at the upper running track may have occurred because of incompatibility in deformation between the flexible steel columns and the brittle masonry units and the associated pounding that occurred between the two components.



(a)



(b)



(c)

Figure 6.14. (a) Damage to CMU wall at upper running track, (b) out-of-plane separation/dislodging of CMU wall blocks, and (c) fallen block in stairwell (photos: Wael Hassan)

CMU blocks dislodged by differential movement with the roof fell down into the stairwell, which was fortunately empty at the time of the earthquake. According to an engineering evaluation provided by the district (PND Engineers, 2018)¹¹, these CMU walls were intended to be partitions providing a hard surface and appear not to have been built according to the design drawings. The 30-foot (9.14-m) stair wall did not have the top lateral bracing details shown in the drawings. However, the evaluation determined this detail would have been insufficient to restrain such a tall, heavy wall under strong shaking, even if had it been installed, and recommended replacement with lightweight materials: steel stud walls and drywall finish.

Minor structural damage or evidence of inelastic structural behavior, such as hairline cracking in joints of reinforced CMU masonry, occurred in 14 schools in Mat-Su school district, including Finger Lake Elementary, Goose Bay Elementary, Meadow Lakes Elementary, Wasilla Middle, Palmer Junior Middle, Palmer High, and Colony Middle. Figure 6.15 shows typical damage of this type. Wasilla Middle School experienced some CMU wall cracking that required further structural investigation. At Colony Middle School, built at the same time as Colony High (designed in 1996, completed in 1988) but with a reinforced-concrete, shear-wall lateral system, the team observed a 1/32-inch to 1/16-inch (0.8–1.6-mm) diagonal crack in a shear wall. This was the only wall the team could observe; others were covered by finishes or lockers or were otherwise inaccessible.

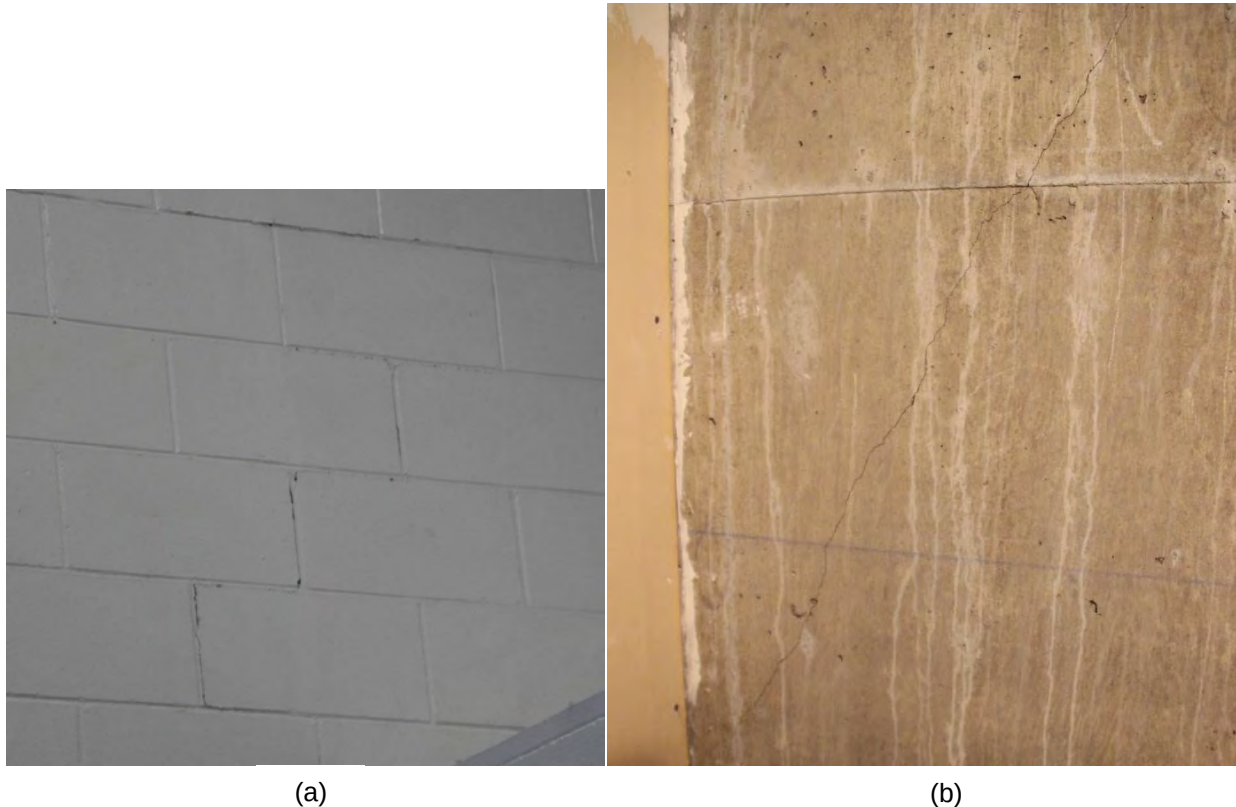


Figure 6.15. Typical minor cracking in reinforced CMUs: (a) Finger Lake Elementary and (b) shear crack in reinforced concrete shear wall, Colony Middle (photos: Chris Motter).

Seven of MSBSD's elementary schools use a standard plan with prominent ramps between levels and are called "ramp" schools. The first and oldest of these reinforced CMU schools, Finger Lake Elementary, experienced minor CMU cracking above classroom doorways (these masonry spandrels were not present in later designs), in the music room wall, and in gymnasium walls. Other ramp schools also experienced similar cracking.

6.4 Nonstructural School Damage

The majority of school damage across both districts was nonstructural. Schools experienced damage to suspended ceilings; lighting; piping; heating, ventilation, and air conditioning (HVAC) systems; mechanical and electrical systems; elevators; doors; windows; and finishes and partitions, as well as contents such as computers and furniture. This damage caused significant disruption and downtime and caused the majority of school closures. All ASD schools experienced at least minor nonstructural damage, including the Girdwood K–8 school southeast of Anchorage that was much further away from the epicentral region. In addition, at least 10 schools had major-to-severe nonstructural damage. In the Mat-Su district, 37 schools had nonstructural damage requiring repairs, including 6 with major-to-severe damage, 12 with moderate damage, and 19 with minor damage. Undamaged MSBSD schools were in areas of light shaking far from the epicentral region. For the purposes of this report, nonstructural damage levels are defined primarily on the basis of the extent of suspended-ceiling damage, which appears to have had the most significant impact on school closures. Damage was considered minor if it was only finish damage, minor lighting damage, or some fallen tiles. Moderate damage included limited instances of ceiling-grid damage, widespread finish damage, or a few significant pipe breaks or leaks. Major damage included any damage that presented a life safety hazard; ceiling failure with falling grid, tile, and lights; major

HVAC, mechanical, electrical, or piping damage; or widespread and significant partition damage requiring replacement. Damage levels were assigned on the basis of review of damage reports and photographs for each school provided by the school districts, as well as field observations by reconnaissance team members.

6.4.1 Ceiling Damage

Of the types of nonstructural damage observed, ceiling damage was the largest contributor to school closures. Damage ranged from minor, with dislodged or fallen tiles or tile damage from movement of fire-sprinkler heads, to moderate-to-significant grid damage at ceiling perimeters, to major damage or destruction with fallen grid members, lights, and air diffusers (Figure 6.16). Damage was so extensive that officials from both districts joked that they had bought up all of the ceiling tile in the state to make repairs in the aftermath of the earthquake.

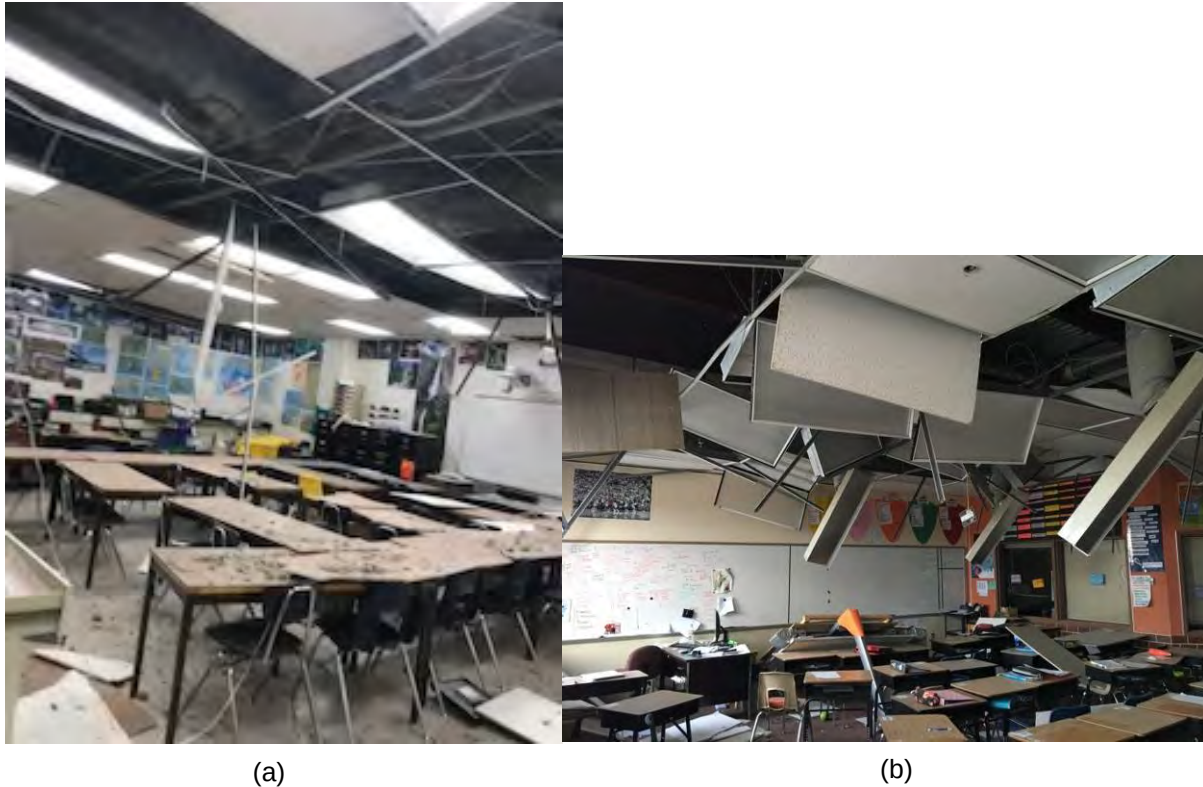


Figure 6.16. Major ceiling damage at (a) Bartlett High fifth floor with fallen grid (note lack of seismic bracing) and (b) at second floor of Colony Middle (photos: (a) ASD and (b) MSBSD).

Schools in both districts had suspended ceilings of various ages, built under code editions with nonstructural provisions ranging from nonexistent to current. Although some upgrades and ceiling replacements took place over the years, many schools still had ceilings with inadequate seismic detailing. As expected, many ceilings with seismic deficiencies performed poorly, especially those in the top stories of multistory buildings, as Figure 6.17 shows.



(a)



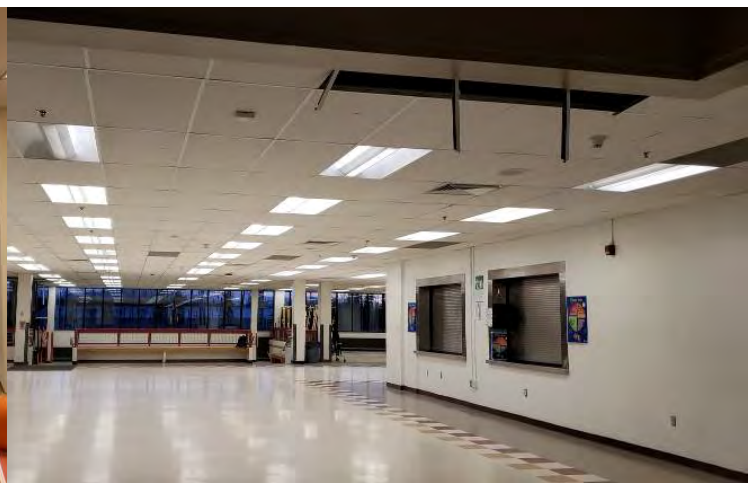
(b)

Figure 6.17. Damaged suspended ceilings with (a) inadequate (Bear Valley Elementary) or (b) nonexistent (Houston Middle) seismic bracing (photos: (a) ASD and (b) Janise Rodgers).

Anchorage schools experienced widespread ceiling damage, with major damage to ceilings in the top (fifth) floor of Bartlett High (Figure 6.16), in Bear Valley Elementary (Figure 6.17), and in some rooms of additional schools. A number of ceilings experienced moderate damage, with grid damage near walls caused by the ceiling swinging and impacting the wall, as Figure 6.18 shows. Interactions with fire sprinklers caused additional damage (Figure 6.19).



(a)



(b)

Figure 6.18. Moderate suspended ceiling damage with grid damage at wall at (a) Bear Valley Elementary, which also had some ceilings with major damage, and (b) Wasilla High School (photos: (a) J. Shaw, ASD, and (b) MSBSD).

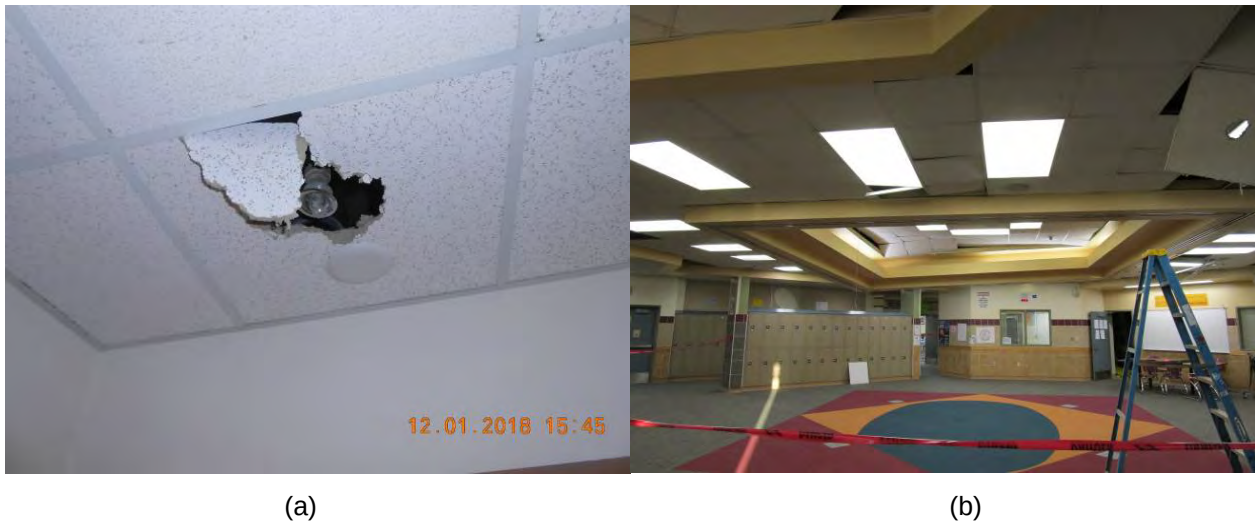


Figure 6.19. (a) Fire-sprinkler drop and head movement with respect to suspended ceiling, damaging the acoustical tile; (b) ceiling damage due to inadequately braced soffit at Dimond High. Note the hole from the fire sprinkler in hanging tile at right (photos: ASD).

Several Mat-Su schools, including Colony Middle (Figure 6.16), Houston Middle (Figure 6.17), and Finger Lake Elementary, suffered major damage to suspended ceilings and integrated elements, such as light fixtures and air-supply diffusers. These ceilings appear to have had little to no seismic bracing. In 2005–2006, MSBSD seismically upgraded ceilings in some middle and high schools, including Colony High, Palmer Junior Middle and High, and Wasilla Middle and High. Ceilings at some of these schools, particularly Colony and Wasilla High, had moderate damage. Notably, Houston Middle and Colony Middle were not upgraded, and ceilings there fared much worse.

Some newer suspended ceiling systems also suffered unexpected damage. The relatively new (2007) suspended ceiling of the Knik Elementary gymnasium, an unusual design with heavy (estimated about 30 lb each) acoustical panels rather than lightweight acoustical tile, experienced major grid damage and lost a number of panels, as Figure 6.20 shows. Children who would have normally been in the gym at that time were elsewhere, fortunately, according to the principal. This incident could trigger redefinition of the “Life Safe” performance level for this type of heavy tile ceiling. Some schools, gyms, and commercial buildings in Southcentral Alaska abandoned this type of ceiling, and the suspended ceiling concept altogether, in their repairs following the earthquake. Some newer ceilings (~2003) at Dimond High in Anchorage also suffered damage at the edges because of movement and because of interaction with an inadequately supported soffit.



Figure 6.20. Ceiling damage at Knik Elementary; this ceiling had unusually thick and heavy panels (photo: MSBSD).

Some schools in both districts also had adhered acoustical tile dislodge and fall during shaking, particularly in gymnasiums, as in Figure 6.21.



Figure 6.21. Fallen adhered acoustical tiles in gymnasium, Eagle River Elementary (photo: ASD).

6.4.2 Damage to Building Systems

Schools in both districts experienced damage to a number of building systems, including HVAC, mechanical, electrical, domestic-water, fire-suppression, fire-alarm, and communications systems. At the 15 Anchorage schools with heavier damage, mechanical, electrical, water, or other building systems typically experienced some damage.

As discussed in the previous section, major-to-severe damage to suspended ceilings was typically caused by a lack of (or inadequate) seismic bracing and detailing, because those ceilings predate modern code provisions. Suspended equipment, piping, and conduits in those ceilings would typically also lack adequate seismic restraints, leading to vulnerability. Air diffusers in suspended ceilings were damaged in schools with major-to-severe ceiling damage. Other suspended ventilation equipment in ceilings was inadequately restrained in some schools and was damaged, and a few schools reported damage to ductwork (see Figure 6.22). At Colony High, a large duct with diffusers rotated, and segments began to separate, creating a falling hazard.

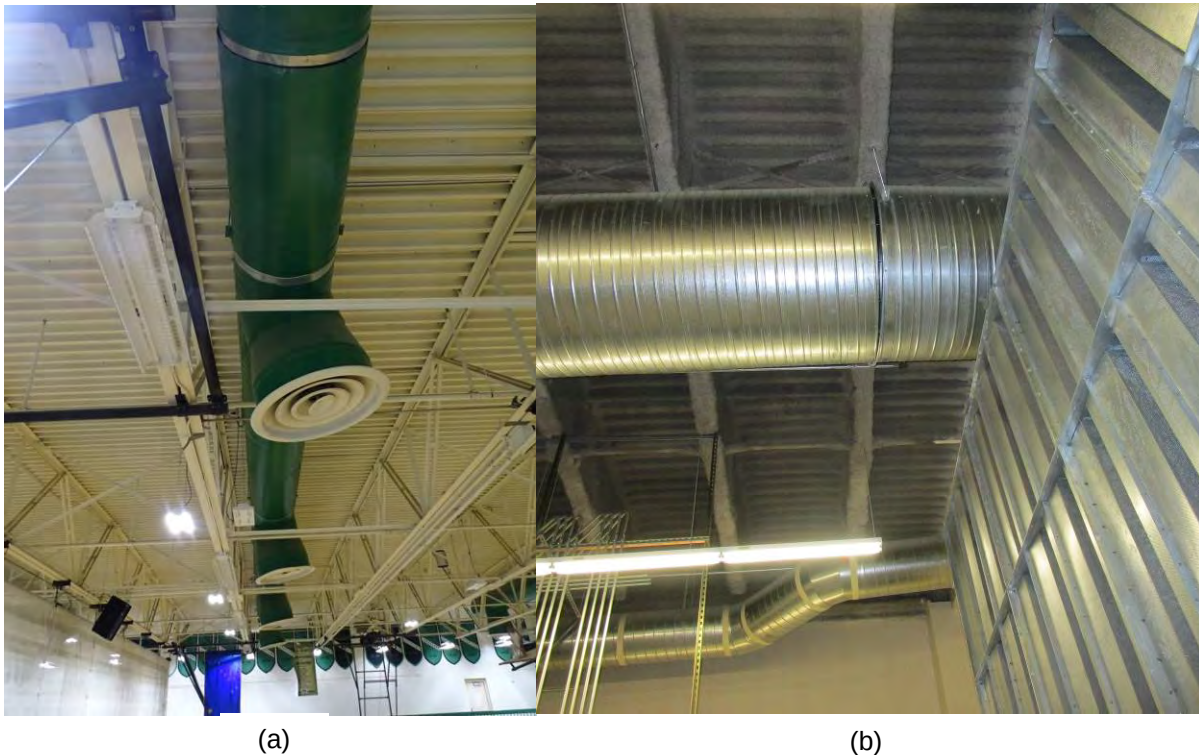
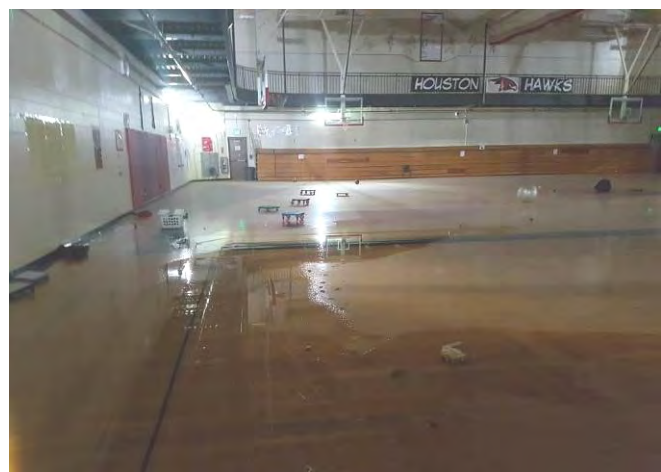


Figure 6.22. (a) Rotation and separation of large duct and diffusers in Colony High gymnasium; (b) separated duct sections at Dimond High (photos: (a) Janise Rodgers and (b) ASD).

Many schools have heating systems with glycol piping above the suspended ceilings. Numerous glycol leaks were reported in both districts, as well as leaks from water pipes in ceilings with the worst glycol leak reported in Gruening Middle in Eagle River (see Figure 6.23). Fire-sprinkler drops damaged tiles or were damaged by differential movement of suspended ceilings, leading to leaks in some schools.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 6.23. (a) Water damage to gymnasium floor at Houston Middle (photo: MSBSD); (b) glycol leak, Gruening Middle (photo: Reid Middleton); and Gruening Middle (c–f) mechanical room piping failure and glycol leak with (e) tank-restraint failure and (f) elbow-connection failure (photos: Wael Hassan).

In addition, a few Anchorage schools had inadequately restrained air-handling equipment that moved or fell from vibration isolators. At Bartlett High, vibration isolators for several pieces of equipment failed (see Figure 6.24). Several gas leaks occurred, but Anchorage schools had automatic seismic gas shutoff valves, installed with Federal Emergency Management Agency (FEMA) mitigation grant funding several years ago, which prevented major problems from occurring because of gas leaks or broken gas pipes.

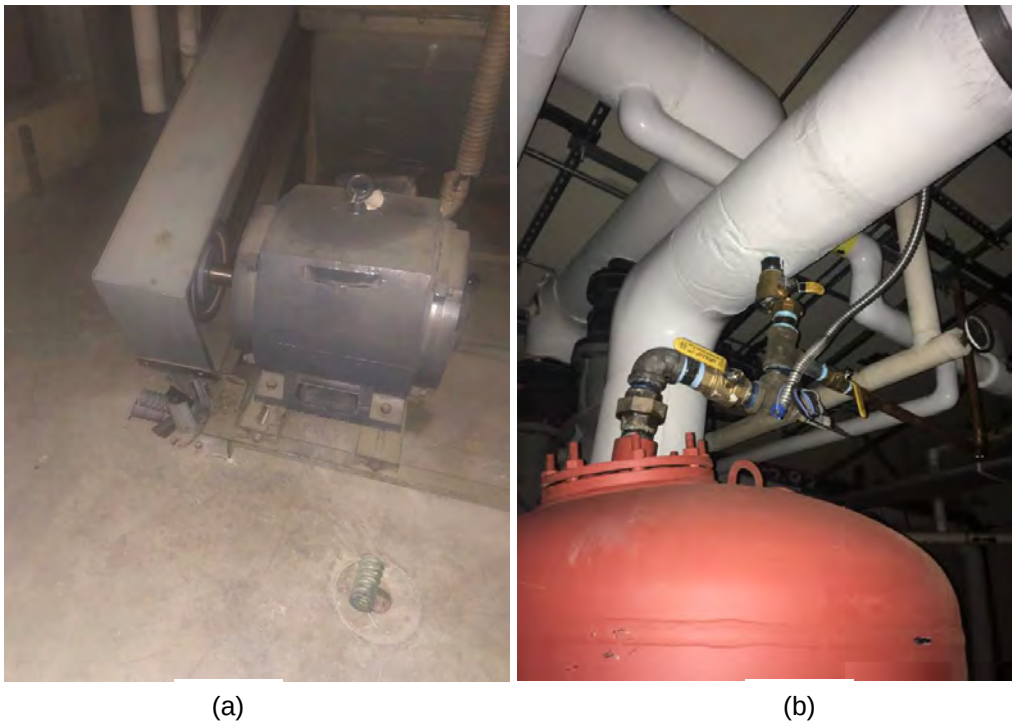


Figure 6.24. (a) Broken nonseismic vibration isolator, Bartlett High; (b) broken pipe connection to unbraced hot water generator, Bear Valley Elementary (photos: ASD).

In Mat-Su schools, Houston Middle experienced damage to multiple building systems, including the fire-alarm and communications systems, as well as several leaks.

6.4.3 Damage to Floors

Damage to nonstructural flooring was observed in multiple schools, including schools in Eagle River, Mat-Su, and South Anchorage. An example of cracking in floor tiles is shown in Figure 6.25. In some cases, damage in floor finishes may have resulted from ground movement. Tile failure near seismic joints was noticed in several structures, including schools throughout the region. Floor finish failure should be viewed with special caution as it might imply diaphragm failure or local slab damage.

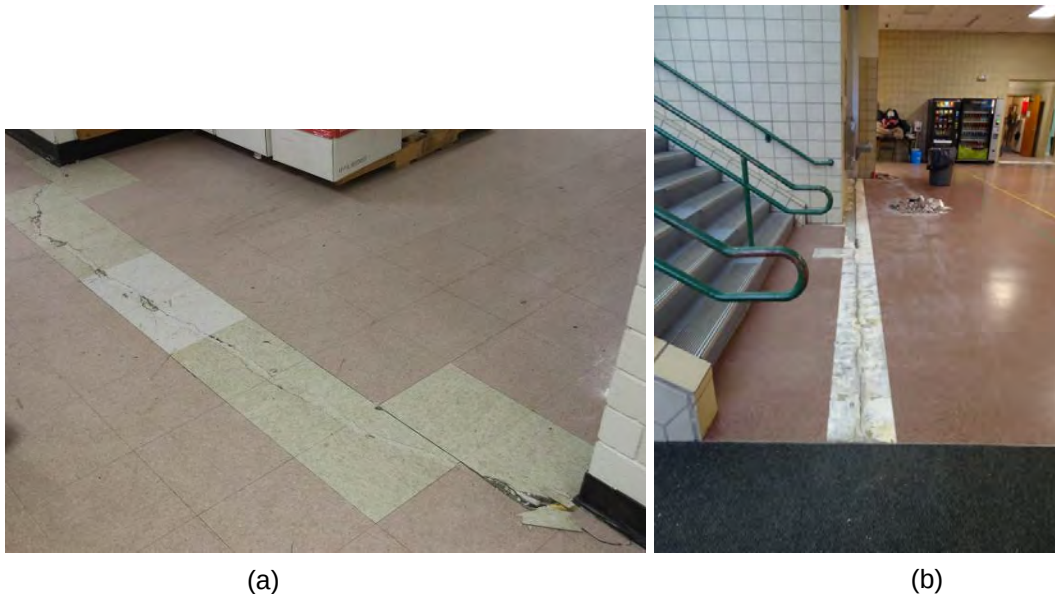


Figure 6.25. Damage to tile floors at (a) Eagle River Elementary and (b) Colony Middle. At Colony Middle, floor tiles were installed over a seismic joint at the lowest floor (photos: (a) Chris Motter and (b) Janise Rodgers).

6.4.4 Damage to Furnishings and Contents

Fallen contents such as books and classroom supplies were common in both districts. The Mat-Su district had anchored all heavy classroom furniture to walls, so there were few instances of contents damage that could have caused serious injury to students. Heavy furnishings are also anchored in ASD schools, but there were a few instances in which furniture had not been anchored and toppled, as shown in Figure 6.26.



Figure 6.26. Toppled bookcase, Bear Valley Elementary (photo: ASD).

6.5 Cost of Earthquake Damage

According to documents presented to the School Board, as of November 2019, MSBSD had expended \$1,794,141, with an additional \$108,202 of encumbered funds, for a total of \$1,902,343. These amounts cover repair of physical damage as well as district staff overtime to assess and repair facilities, engineering and technical services, and costs to relocate students from severely damaged Houston Middle School to nearby Houston High. These amounts do not include the Houston Middle School classroom-wing replacement and retrofit/repair of the gymnasium and administrative wing, estimated at \$28,884,817 and approved by the School Board on August 21, 2019 (MSBSD School Board, 2019).¹² With the Houston Middle School project added, MSBSD is expected to spend over \$30 million to address damage from this earthquake.

MSBSD has several sources of funding available to cover these costs. On December 4, 2018, the Mat-Su Borough Assembly adopted Emergency Ordinance 18-112, which reappropriated \$5,817,599 from the School Bond Interest Income Fund and \$2,302,157 from the School Site Acquisition Reserve, making \$8.1 million in emergency funds available to address earthquake damage to Mat-Su schools. On January 15, 2019, the Mat-Su Borough Capital Projects Department authorized the district to expend \$2 million for earthquake-related expenditures. MSBSD had earthquake insurance with a 5% deductible and will be able to draw on insurance to fund a portion of the Houston Middle School retrofit project. The School Board resolution approving the Houston Middle School retrofit project (MSBSD School Board, 2019) anticipates covering the costs using a combination of insurance funds, remaining Borough emergency funds, FEMA funds, and state capital improvement funding for which the district has applied. The district designated the Houston Middle project as its highest priority in its Capital Improvement Plan.

As of April 2019, the ASD had spent \$3,915,960.81 to address earthquake damage across all sites, and projected that they would spend an additional \$151 million over time (ASD, 2019b).¹³ For instance, the repair and retrofit of Gruening

Middle School alone is projected to cost \$42 million. The 2019 Capital Improvement Plan includes earthquake safety improvements in numerous upgrade and maintenance projects such as roof replacements (ASD, 2019c),¹⁴ and Anchorage voters approved a school bond containing \$4 million designated for earthquake recovery in Chugiak and Eagle River schools (ASD, 2019d).¹⁵

6.6 School Closure and System Resilience

ASD and MSBSD closed all schools the day of the earthquake, sending students already at school home. Figure 6.27 shows school facility reopening curves for both districts.

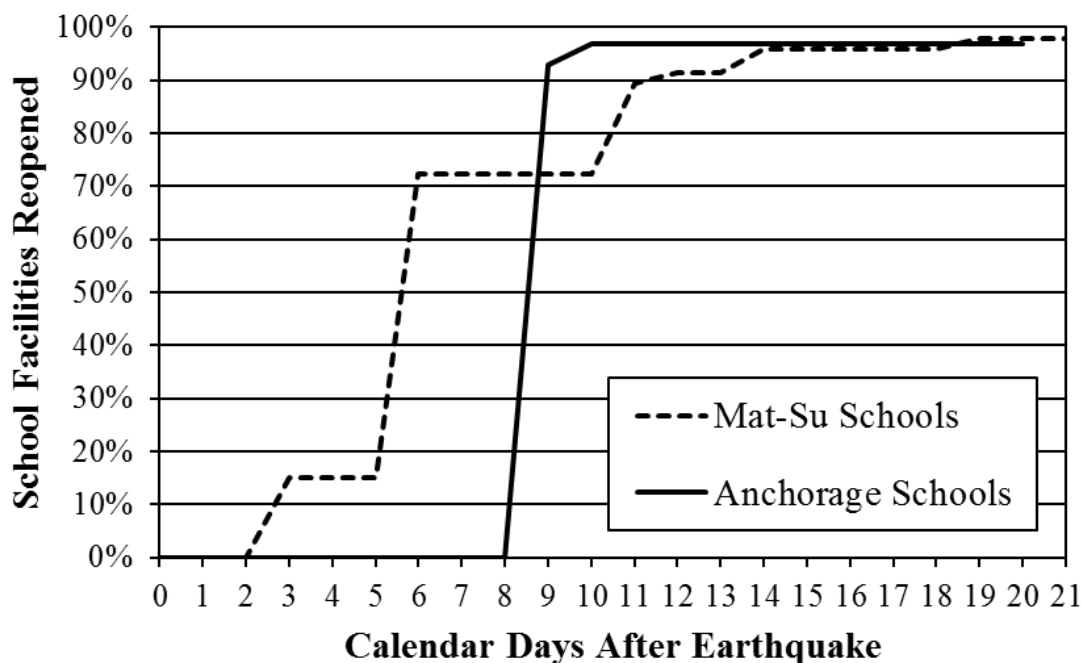


Figure 6.27. School facility reopening curves.

ASD and MSBSD pursued slightly different strategies for reopening schools, partly because of differences in the fraction of district schools that were strongly shaken; as previously discussed, MSBSD covers a large geographic area extending northward and eastward from the epicentral region. MSBSD reopened 7 schools (15%) with minimal to no damage located outside the strongly shaken areas on Monday, December 3, but reopened the majority (27, 57%) to students Thursday, December 6, after cleanup. Initially, all ASD schools were shut down for inspection—almost all were in areas that had been strongly shaken—until December 5. A few schools were identified as having more serious damage, so ASD kept all schools closed until December 10, even those with minor damage. Teachers and staff were required to report back December 5 to help with cleanup. In both districts, a small number of schools remained closed beyond a week, and the four schools previously mentioned (three in Eagle River and one in Houston/Big Lake) were closed for the remainder of the school year, with students shifted to other facilities.

6.7 Student Population Behavior and Injuries

Middle and high schools were in session at the time of the earthquake, and despite extensive ceiling damage, including falling ceiling tiles, metal light fixtures, books, and supplies (heavy furniture was typically anchored), both school districts reported very few injuries. MSBSD schools reported 13 student injuries and 2 staff injuries, while ASD schools reported 3 student injuries and 11 staff injuries, which are detailed in Table 6.1.

Table 6.1. Reported student and staff injuries.

School	Student Injuries		Number of Staff Injuries	Injury Type (Number)
	Number	% of students*		
MSBSD				
Colony Middle	11	1.41	0	Struck in head by unknown object (1) Struck by ceiling tile on back (1) Struck in arm by ceiling tile (2) Right leg hit by drywall and left leg hit by pole in gym (1) Leg injury, cause unknown (1) Shock, dizziness, or stress (3) Low blood pressure (1) Asthma due to dust (1)
Houston High	1	0.29	1	Concussion from falling books and hitting head on desk Head injury from falling ceiling tile (staff)
Houston Middle	0	0	1	Knee injury occurred while getting under a desk for protection
Teeland Middle	1	0.13	0	Leg injury from students stepping on it while trying to get to the wall
ASD				
Alpenglow Elementary	1	Not applicable	0	Student in before-school program struck by falling debris
Bartlett High	0	0	2	Struck by falling debris (1) Employee jammed finger while getting under desk (1)
Begich Middle	0	0	1	Struck knee while getting under desk
Central Middle	0	0	1	Struck knee while getting under desk
Denali Elementary	0	0	1	Struck by falling debris
Fairview Elementary	0	0	2	Push by student causing staff to fall (1) Tripped over items on the floor from earthquake (1)
Mears Middle	0	0	1	Strained muscle when diving under desk and craning neck
King Tech High	0	0	1	Pulled muscle during the earthquake
Whaley School	0	0	1	Bumped head and left arm on the desk that was shaking during earthquake
Wendler Middle	2	0.4	0	Speaker fell hitting student's finger (1) Student had a bloody nose either from diving under desk or desk shaking and hitting nose (1)

*Because school was cancelled the day of the earthquake, MSBSD attendance data are not available, and Anchorage data are not broken out by school. Instead, injury rates were calculated using the enrollment at each school.

ASD's policy for reporting injuries is to ask for incident reports for any injury that requires more than basic "comfort care." The district asks that an incident report be completed any time the nurse feels it appropriate to call and notify a parent of an injury. The district also asks that all employees who sustain injuries at work complete a Workers Compensation packet, regardless of whether or not treatment will be sought.

Statements by the school districts, media reports, and field interviews with administrators, as well as review of available social media footage (McBride, *pers. comm.*, 2019), indicate that students taking protective action under desks, as they had been trained to do during regular "Drop, Cover, and Hold On" drills, was a key reason for the low number of injuries. This is despite extensive ceiling damage that caused tiles, portions of the grid, light fixtures, and air diffusers to fall and swing into the space students would normally occupy. School preparedness programs that include drills empower students and teachers to know what to do and to act rapidly. Widely shared footage from an Anchorage school shows all students under desks within four seconds (McGee, 2019¹⁶; McBride, *pers. comm.*, 2019), an excellent example of preparedness in action. Footage from Mat-Su shows students similarly under desks during the shaking. It is noteworthy,

however, that many incidents of large CMU-block falls, heavy wooden-ceiling-tile falls, and similar heavy nonstructural falling hazards occurred in areas without safe cover nearby, such as in stairs and gymnasiums. Few to no students, mercifully, were in these locations at the time of the earthquake. Had this earthquake happened while students were present, there could have been serious injuries and even loss of life.

Structural performance that kept buildings standing and, in many cases, structurally undamaged (or with minimal damage/nonlinear behavior) was the most important factor in protecting students. It is worth mentioning, however, that several schools experienced serious structural damage that might have led to partial collapse had shaking been just a bit stronger or of longer duration. It was fortunate that no collapses, injuries, or fatalities occurred. It is also noteworthy that classroom environments in both districts had been made much safer by anchoring large and heavy furnishings, such as bookshelves, and classroom equipment, such as smartboards.

6.8 Comparison of Predicted and Observed School Performance

In 2015, FEMA funded, and the Earthquake Engineering Research Institute and Alaska Seismic Hazards Safety Commission supported, a pilot rapid visual screening (RVS) study of 7 MSBSD schools and 15 schools in the KPBSD. ASD follows different procedures for assessing schools and conducts an *ASCE-41* Tier 1 assessment for all schools undergoing significant repairs or renovations, such as roof replacements, so that seismic upgrades can be incorporated.

The MSBSD screening study used *FEMA 154, Rapid Visual Screening of Buildings for Potential Seismic Hazards, Second Edition* (FEMA, 2002),¹⁷ and reviewed additional information, including, most significantly, the structural drawings (Berry et al., 2015).¹⁸ MSBSD selected seven of the oldest schools, with 17 buildings including additions, omitting schools that had recent major additions or renovations. Because of the method of selecting buildings on the basis of age alone (Weese, *pers. comm.*, March 2019) rather than by code benchmark dates, the set of buildings screened did not represent the district's full stock of buildings that predate recent codes. The RVS effort identified 9 of the 17 buildings screened as having an unacceptable level of seismic risk, meaning more than a 1% probability of collapse using FEMA's criteria (Berry et al., 2015). Four wood-frame "box"-type elementary schools built in the late 1970s and early 1980s using the same standard plans were found to have very low probabilities of collapse (0.002%). *FEMA 154*'s RVS is an intentionally a conservative screening tool, designed to identify buildings with potentially significant seismic vulnerabilities and to refer them for further investigation.

A comparison of RVS results with earthquake damage, available in a separate report (Rodgers, 2019),¹⁹ shows that the RVS pilot study did not cover the schools with the most damage. The schools not assessed during the RVS include Houston Middle School, which was declared structurally unsafe and closed for the remainder of the year, and Colony High School, which had CMU wall damage and ductwork damage that closed the gymnasium to students. Of the 13 MSBSD school facilities closed 10 days or more by earthquake damage, only 2 were part of the RVS pilot study, although the primary reason for lengthy closures was nonstructural damage. Older but post-benchmark wood-frame schools performed well, as expected. There are indications that shaking was not as strong at some of the RVS schools in Wasilla and Palmer, so the fact that schools identified by the RVS as having higher risk remained undamaged does not necessarily mean that they lack vulnerability.

6.9 School Earthquake Safety Program Effectiveness

The combination of life safety structural performance, anchoring of heavy furnishings, and student preparedness and drills to practice protective action appears to have protected students. Some schools experienced potentially life-threatening damage, such as falling CMU blocks, but no students were in those areas at the time. Older schools must be seismically evaluated and strengthened or replaced if needed. If districts want to reduce lost instructional time, and prevent injuries, however, more attention must be paid to ensuring that nonstructural components (i.e., ceilings) have adequate seismic design.

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- ² Mat-Su Borough School District (MSBSD), 2019a. School district website, available at www.matsuk12.us (accessed March 2019).
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7 PERFORMANCE OF HOSPITALS AND HEALTH CARE FACILITIES

7.1 Overview

There are 24 major hospitals in Alaska, 5 of which are designated trauma centers. Anchorage is the largest city in the United States that lacks level II trauma centers for the general population. Three major hospitals serve the municipality of Anchorage: Alaska Regional Hospital (ARH), Providence Alaska Medical Center (PAMC), and Alaska Native Medical Center (ANMC), along with the Veterans Affairs (VA) Hospital. ANMC is the only level II trauma center in the state, with capacity far less than demand, even for the city of Anchorage, as it is designated only for Alaska Natives. Figure 7.1 shows ARH, PAMC, ANMC, and Matanuska-Susitna (Mat-Su) Regional Medical Center.



(a)



(b)



(c)



(d)

Figure 7.1. (a) ARH (photo: NEESER Construction, Inc.), (b) PAMC (photo: Architects Alaska), (c) ANMC (photo: PDC Engineers), and (d) Mat-Su Regional Medical Center (photo: unknown).

For a few days following the earthquake, all three hospitals received patients with very minor injuries related to the event. ARH is a multibuilding, for-profit, 250-bed facility that started in 1976 at its current location. ANMC is a tribally owned and operated nonprofit public facility of 167 beds that was established in 1997 and is considered one of the largest hospitals in the public U.S. health care system. PAMC is the largest hospital in Alaska, with 401 beds, 850 physicians, and a megacampus of more than 10 buildings in Anchorage, with several off-site facilities and clinics in Eagle River and Mat-Su Valley. PAMC is a missionary hospital that dates back to 1939 in Anchorage; however, PAMC started at its current campus near the University of Alaska, Anchorage (UAA) in 1962. The Blood Bank of Alaska (BBA) main center in Anchorage is a designated essential facility that was constructed in 1982. Many other smaller medical centers and clinics utilize office buildings and strip malls that had the typical structural and nonstructural damage in these buildings described in previous chapters.

The ground-motion peak ground acceleration (PGA) in the close vicinity of PAMC and ANMC is estimated at 0.21g on the basis of the free-field station at UAA. ARH may have experienced 0.25g–0.32g, based on the ShakeMaps presented in earlier chapters.

The Mat-Su Regional Medical Center is a 74-bed hospital opened in 2006, which replaced the older facility in Palmer. It is the primary acute care hospital serving the Mat-Su Borough and is its only level IV trauma center. The hospital has two privately managed medical office buildings (MOBs) adjacent to the hospital and connected via corridors. MOB 1 is a four-story building built around the time of the main hospital, while MOB 2 is a newly built two-story steel-braced frame building. Mat-Su Regional is located near the intersection of the Parks Highway and Trunk Road. The nearest strong-motion station, approximately 7.5 km away at the Alaska Tsunami Warning Center in Palmer, recorded motions of 0.14g PGA, with calculated peak ground velocity of 11 cm/s, indicating that shaking at the hospital was likely moderate. Mat-Su Regional has three associated urgent care clinics (Wasilla, Knik, and Palmer), as well as medical offices and a rehabilitation center in other locations. In addition, the valley has private urgent care facilities, such as the Medical Group of Alaska's Capstone urgent care clinic in Wasilla and family medicine facilities. The group also has facilities in Eagle River and Anchorage.

The three major hospitals in Anchorage had light-to-heavy nonstructural damage, several water leaks and flooding, and some equipment damage, although emergency rooms (ERs) remained open, except for one that was closed briefly to repair water damage. All three hospitals cancelled elective surgeries and noncritical appointments. ARH experienced the most visible damage with water flooding that affected large segments of floors and ceilings because of firefighting system failure that led to nearly shutting down two outpatient clinic buildings on campus, which have partially resumed operation with an estimated 20%–30% capacity 2 weeks after the earthquake. One of the three major Anchorage hospitals experienced structural core-wall shear cracks in its pre-1980 building. At another Anchorage hospital, major boiler failure occurred, leading to building flooding, electric panel failure due to short-circuiting, and a consequent fire alarm activation. The Mat-Su Regional Medical Center remained open but experienced minor structural damage, glycol leaks leading to a shutdown of the heating system, and some piping failure due to water tank sliding, along with other minor nonstructural damage. The VA Hospital experienced some cosmetic sheetrock cracking at the second floor only and remained operational.

Overall, the hospitals' performance was acceptable in both Anchorage and the Mat-Su Borough, but this should be viewed in light of the relatively small-to-moderate shaking intensity recorded near hospital locations (0.14g–0.32g), which was less than the design-based earthquake shaking.

Information on Mat-Su Regional performance was obtained through field interviews with health system and MOB personnel, damage information provided by hospitals, and by limited field reconnaissance in the MOBs on December 11, 2018. Information on Anchorage hospitals was obtained via extensive field reconnaissance, interviews with building engineers and managers, and official hospital damage reports provided by hospitals, borough assessors, and media outlets.

7.2 Hospital Structural Impacts

All three Anchorage hospitals hired professional structural engineers immediately following the event to conduct self-structural assessment. ANMC and PAMC soon reported no serious structural damage, but it took a more thorough investigation at ARH to clear the buildings for full functionality, apparently because of some structural concerns. Mat-Su Regional was inspected by a structural engineer and had only minor structural damage. BBA, which is a designated immediate-occupancy essential facility, suffered limited structural damage. The structural-damage photos in this section are presented without association with particular Anchorage hospitals.

Diagonal shear cracks in concrete core and structural walls appeared in many locations at first and second stories of the main patient building at one of the Anchorage hospitals (Figures 7.2, 7.3, 7.4, and 7.5). The crack width was minor, on the order of 1/32 to 1/16 of an inch. However, crack length varied from a few inches to 6 feet, extending across nearly two-thirds of the wall height. Shear cracks appeared as diagonal or cross-shaped diagonal cracks. There was no clear evidence of crack penetration across wall thickness, despite apparently good alignment of cracks on both faces of

particular walls. This main hospital building was operational, despite the widespread shear cracks. The building was constructed in the 1970s, with few additions and renovation projects after 1980.



Figure 7.2. Concrete core wall cross-shaped shear cracks in main building of an Anchorage hospital. These cracks are sample of many similar cracks at different concrete shear walls at level 1 of the hospital (photo: Wael Hassan).



Figure 7.3. Concrete shear wall cross-shaped shear cracks in the main building of an Anchorage hospital (photo: Wael Hassan).



Figure 7.4. Minor concrete core wall diagonal shear crack in the main building of an Anchorage hospital; photos were taken inside the elevator shaft (photos: Wael Hassan).



Figure 7.5. Concrete core wall diagonal shear cracks in the main building of an Anchorage hospital (photo: Wael Hassan).

Expansion and seismic joints at all three Anchorage hospitals experienced light-to-moderate damage as per the design intent, mostly to the joint finishes, protecting structural components efficiently (Figure 7.6). At one of the parking floors at the ground level of one hospital, there were gypsum ceiling cracks above exterior concrete columns, which might have implied hidden structural damage in the floor diaphragm (Figure 7.7). Some minor flexural cracks appeared in spandrels and exterior columns of the same building (Figure 7.8).



Figure 7.6. Examples of seismic joint damage at an Anchorage hospital (photos: Wael Hassan).

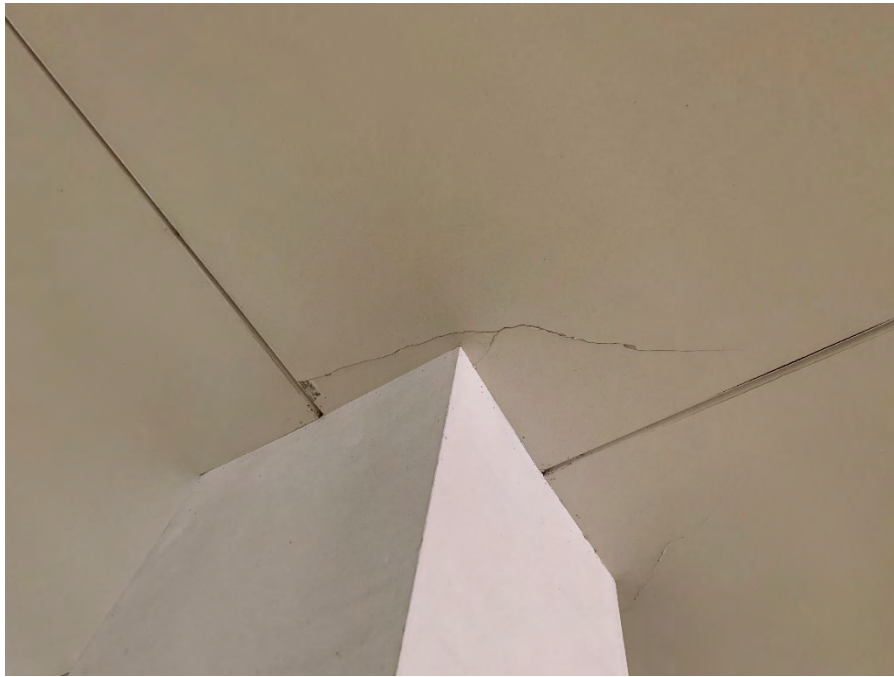


Figure 7.7. Gypsum-finish cracking above a concrete column in an Anchorage hospital parking structure might imply hidden diaphragm or concrete slab damage. This crack was typical above many exterior columns (photo: Wael Hassan).



Figure 7.8. Flexural cracking in spandrel concrete in an Anchorage hospital's parking structure. Ceiling-finish cracking here might imply hidden concrete slab damage (photo: Wael Hassan).

At Mat-Su Regional, no significant structural damage was reported to the hospital or the neighboring MOB 1. MOB 2 experienced minor flexural cracking of the concrete slab on metal decking longitudinally along beams and in the slabs (Figure 7.9); reconnaissance team members were told this cracking occurred because of the earthquake. This cracking was visible in an unfinished floor that allows for future expansion. It is unclear whether the cracks were present prior to the earthquake and were widened by it or whether they were only due to the earthquake response of the building. Similar cracking appeared in mechanical-room slabs in both major Anchorage hospitals, BBA, and Mat-Su Valley Providence Cancer Center and was similarly attributed to the earthquake (Figure 7.10).



Figure 7.9. Slab cracking viewed from the second floor of Mat-Su Regional MOB 2, attributed by building personnel to the earthquake (photo: Janise Rodgers).

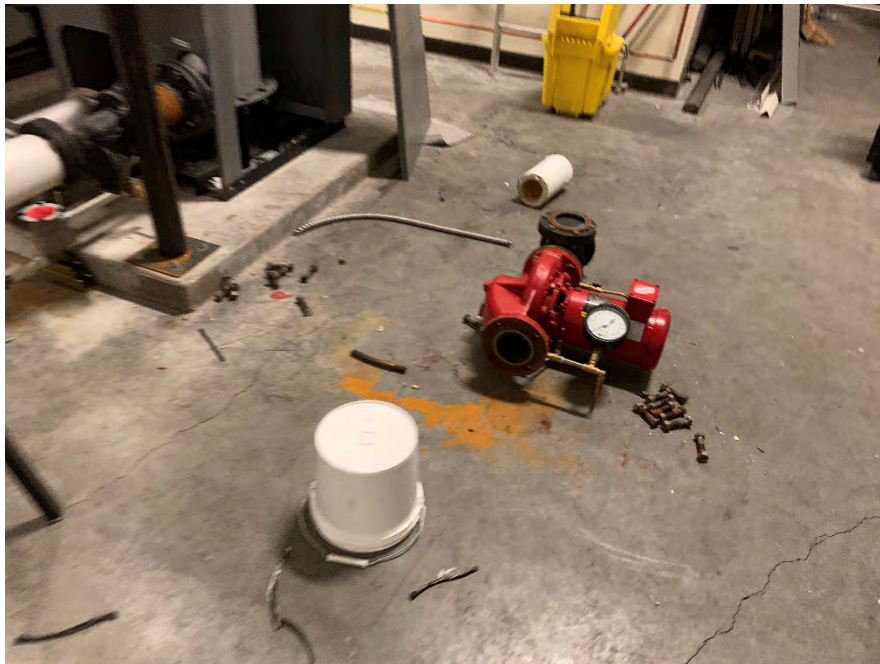


Figure 7.10. Slab cracking viewed from the fourth-floor mechanical room in a hospital in Anchorage, attributed by building personnel to the earthquake (photo: Wael Hassan).

A half-inch-wide flexural crack and concrete crushing occurred at the top of the stairs leading to the mechanical-room penthouse of the BBA (Figure 7.11). The crushing is apparently due to the relative movement of the stair flight against the rigid slab of the mechanical room without a seismic joint. Stringer's bolts below that stair suffered shear failure. Ground failure occurred at one of the Anchorage hospitals, leading to some concrete stairs and pavement cracks and significant interior floor and finish damage (Figure 7.12).



Figure 7.11. Cracking and crushing of concrete at stair flight-landing interface, BBA (photos: Wael Hassan).



Figure 7.12. Geotechnically related structural damage in a hospital in Anchorage (photos: Wael Hassan).

A good practice lesson worth mentioning is the observation by the structural retrofitting engineer that Parking Structure PS2 at PAMC had concrete parapets connected to their adjacent columns throughout the building, creating short/captive columns that could have possibly failed. Besides fiber-reinforced polymer (FRP)-retrofitted concrete columns, a main component of the retrofit was to isolate the parapets from columns via elastic material (Figure 7.13). The FRP columns did not show any sign of debonding. Some flexural and flexural shear cracks appeared in some of the column tops at PS2, as well as unconfirmed shear wall cracks and concrete parapet shear cracks appearing (Figure 7.14).



(a)

(b)



(c)

(d)

Figure 7.13. (a) PAMC Parking Structure 1, with building retrofitting via (b) FRP wrapping. (c) No signs of debonding were observed following the earthquake. The retrofitting project included (d) separating the concrete parapet from the column with elastic material to avoid a short-captive-column condition. (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)

Figure 7.14. PAMC Parking Structure 1, with (a, b) flexural shear and flexural cracks in concrete columns, a (b) flexural and bond crack/water leak at a concrete expansion-joint column, a (c) concrete shear wall crack not confirmed to be due to this quake, and a (d) concrete parapet shear crack. (photos: Wael Hassan).

7.3 Hospital Nonstructural Impacts

The hospital building at Mat-Su Regional experienced minor-to-moderate nonstructural damage, including a significant glycol leak that shut down the heating system. The seismic sensor in the elevator shut down elevator operations. The hospital remained functional. MOB 1 had a major gas leak caused by an unanchored boiler in the rooftop mechanical penthouse shifting and breaking the gas line (Figure 7.15). The building was evacuated. In addition, water and glycol leaks occurred in this building, including a fourth-floor water-line break that caused significant flooding down into the building.

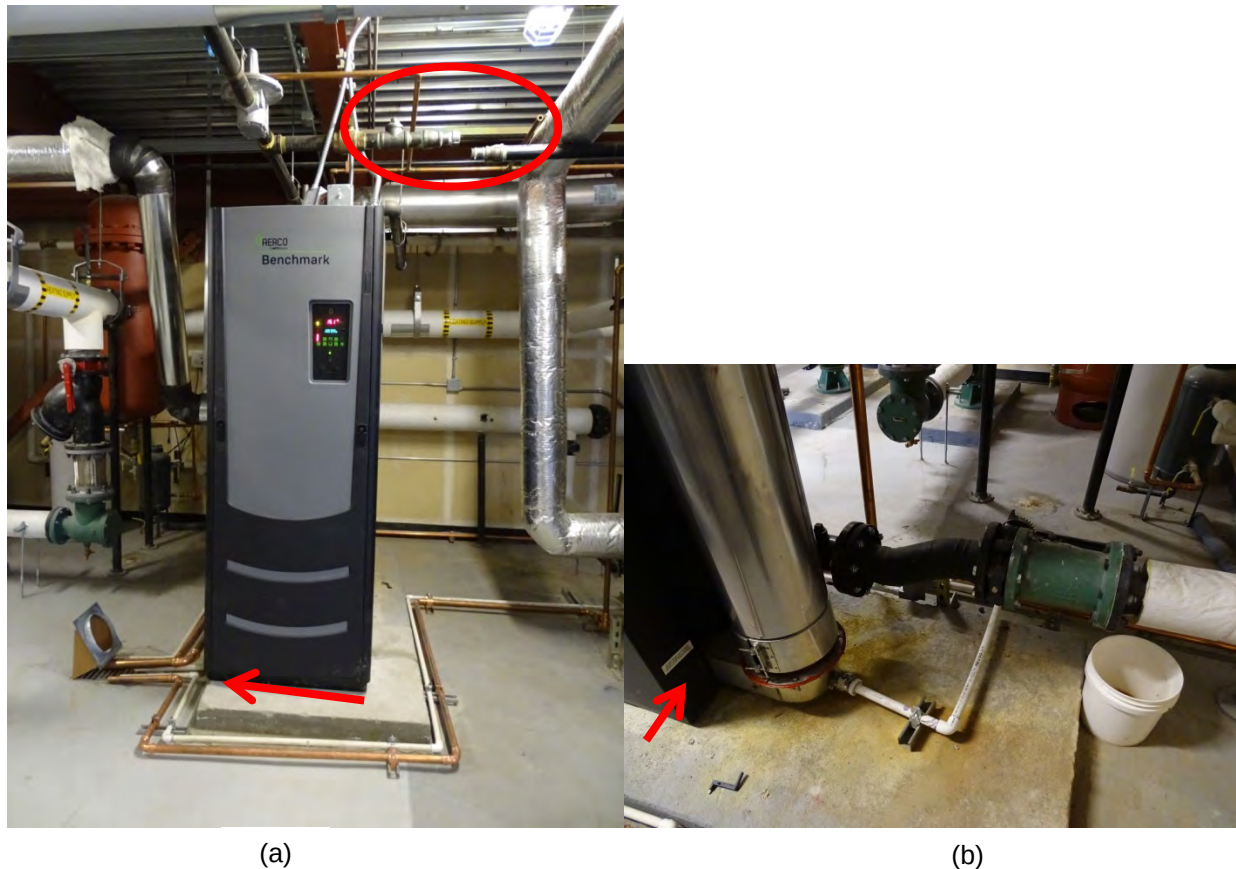


Figure 7.15. (a) Boiler in Mat-Su Regional MOB 1 penthouse shifted to left, with breaking gas line at top right. The ensuing major gas leak forced a building evacuation. (b) Back of same boiler with PVC pipe bent past 90 degrees because of movement (photos: Janise Rodgers).

ARH had moderate-to-heavy nonstructural damage due to a relatively higher PGA and older age. ANMC experienced minor nonstructural damage. PAMC experienced minor-to-moderate nonstructural damage, including moderate water flooding. Severe water damage in multiple locations in both ANMC and ARH occurred, disrupting some operations. The VA Hospital had only cosmetic nonstructural damage, not affecting operations. BBA experienced heavy water damage and minor nonstructural damage.

7.3.1 Water Damage

MOB 1 at Mat-Su Regional had domestic water and glycol leaks, including a leak in the mechanical penthouse and a water leak on the fourth floor, that caused flooding down to the first-floor outpatient surgery center and other specialty areas in the building, including the cancer center. Extensive cleaning and remediation were required, including the removal of floor finishes and drywall, as shown in Figure 7.16. This remediation was ongoing during the EERI Team reconnaissance visit on December 11. At Mat-Su Regional's Wasilla clinic location, glycol lines in the ceiling broke and inundated the top floor.

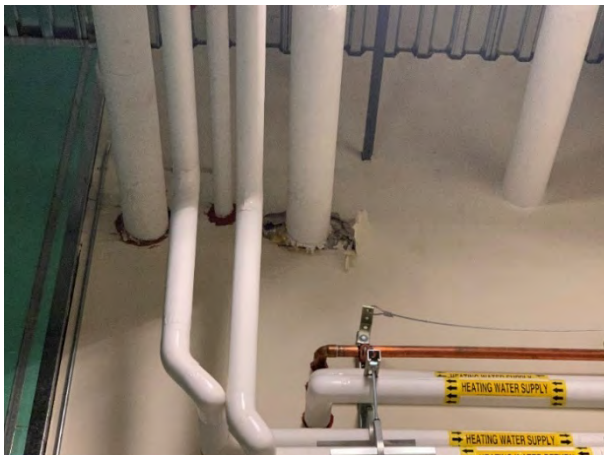


Figure 7.16. Remediation of damage due to water and glycol leaks at Mat-Su Regional MOB 1 on December 11 (photos: Janise Rodgers).

ARH experienced water damage at several locations because of sprinkler-head failure and fire-suppression-piping failure. Two of the major ARH outpatient buildings, B and C, suffered the most water damage, which affected large segments of floors and ceilings because of firefighting system failure that led to nearly shutting down the two buildings, which have partially resumed operation with an estimated 20%–30% capacity 2 weeks after the earthquake.

ANMC experienced water leaks at multiple locations. One of the most serious flooding incidents was in the penthouse mechanical room, which was caused by boiler connection failure that flooded several floors of the hospital building because of water leakage through walls and floors.

PAMC experienced water damage at isolated locations because of sprinkler-head failures. The most significant was in main patient building, Tower D, the oldest on campus. The fourth-floor fire suppression system experienced sprinkler and pipe connection damage that led to flooding an area of 20 by 12 feet, with 2-inch average water depth in the floor below and heavy water damage to the ceiling (Figure 7.17). The water leaked into one of the elevator shafts, leading to the elevator malfunctioning.



(a)



(b)



(c)



(d)



(e)

Figure 7.17. (a) Damage to partition wall due to pipe movement that caused a lack of clearance; (b) water-pipe leak at Anchorage hospital; (c) water-pipe damage at Anchorage hospital; (d) elevator out of service due to water leaks inside the shaft, counterweight damage, or dislocation (photos: Wael Hassan); and (e) duct connection failure at PAMC (photo: PAMC).

The BBA suffered serious rigid-connection water-pipe damage and heat-exchanger rigid-union connection damage in the penthouse mechanical room that led to severe glycol and water flooding, covering large areas of the second floor level below, damaging the ceiling significantly and penetrating to the first floor (Figures 7.18 and 7.19). A 3-inch cast-iron drain piped throughout the building was connected with no-hub fittings, and many of these fittings pulled apart. Of highest concern were the fittings connecting the floor drains of the penthouse, as well as the roof drains. These pipes drained the water and glycol from the penthouse through the drop ceilings onto the second floor. This resulted in damage to ceilings, walls, floors, five computers, and four phones. In the process of drying leaked water and glycol in the BBA, 1,400 gallons of water were pumped out.



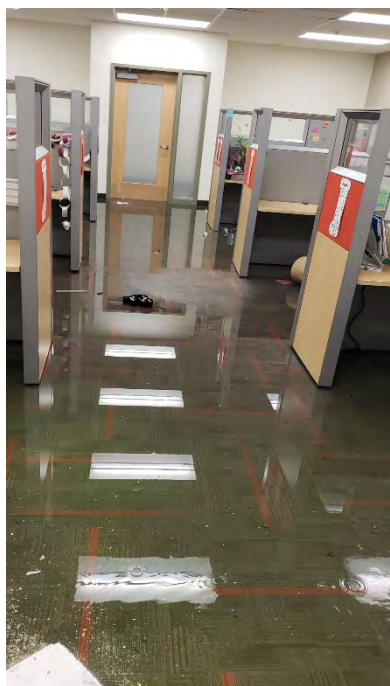
(a)



(b)



(c)



(d)



(e)

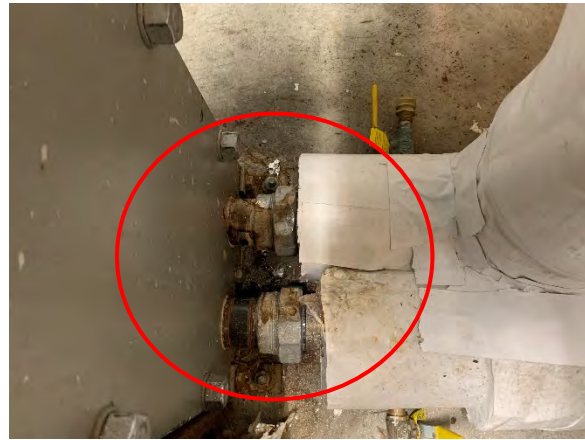


(f)

Figure 7.18. Water damage at BBA: (a) mechanical-room flooding, water leak in (b) ceiling and second-floor hallway and (c) office, 2-inch-deep water flood in (d) offices and (e) hallway, and (f) ceiling damage (photos: BBA).



(a)



(b)



(c)



(d)



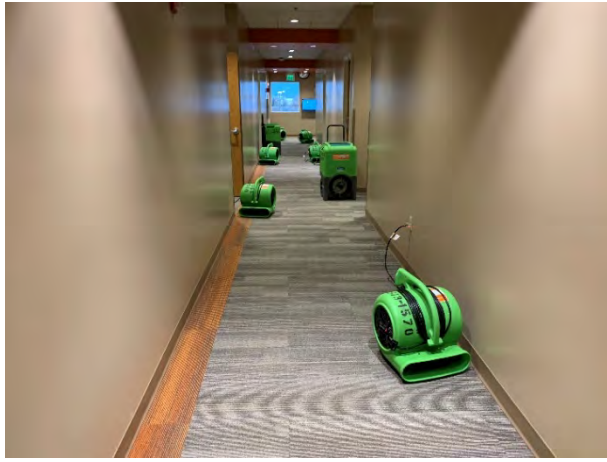
(e)



(f)

Figure 7.19. Mechanical room at BBA: (a) air-duct connection failure, (b) heat-exchanger connection damage, (c) heat-exchanger glycol flooding and damage, (d) stiff-pipe connection failure, (e) water-pipe damage due to collision with stiff out-of-plane steel members, and (f) stairwell drywall damage (photos: Wael Hassan).

In one of the hospitals in Anchorage, the heavy water damage affected operations of some areas, such as radiology and imaging outpatient facilities by causing damage to significant electric wiring and panel hardware and leading to movement of the computed tomography (CT), magnetic resonance imaging, or X-ray units to off-campus locations (Figures 7.20 and 7.21). In another hospital, water flooding resulted in electrical short circuits and electrical panel damage, triggering fire alarms right after the earthquake (Figure 7.22).



(a)



(b)



(c)



(d)



(e)



(f)

Figure 7.20. Water damage impacts at Anchorage hospitals: (a, b) air blowers used to dry major flooding, water leaks on (c) floors and (d) walls, (e) flood-extension marking, and (f) a water leak from fourth-floor failed sprinklers at PAMC (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)

Figure 7.21. (a) Water damage to the ceiling and (b) a broken water pipe at an Anchorage hospital, (c, d) water flooding of the radiology facility at an Anchorage hospital (scanning equipment was affected and moved to an off-site location), and (e) damage to entire electrical wiring due to water flooding (photos: Wael Hassan).



(a)



(b)



(c)



(d)



(e)

Figure 7.22. (a) Mechanical unit sliding in an Anchorage hospital with (b) detail shown; (c) the same hospital mechanical room with water-boiler connection failure due to boiler sliding with (d) detail shown; and (e) triggering of a fire alarm caused by an electrical panel short-circuiting at the floor below because of water damage from the boiler above (photos: Wael Hassan).

The PAMC Imaging Facility in Mat-Su and the clinic facility in Eagle River both suffered severe water and glycol damage.

7.3.2 Equipment Damage

At Mat-Su Regional MOB 1, an unanchored boiler in the rooftop mechanical penthouse moved several inches, which broke the gas line attached to the top of the boiler. The resulting leak forced the evacuation of the building, although the hospital next door remained in service. Elsewhere in the penthouse, several pipes shifted on the hangers, and both glycol and water leaks were reported. The elevator was also out of service.

ARH suffered several pieces of electrical and mechanical equipment damage, especially in the outpatient buildings B and C, primarily due to water damage. Similarly, ANMC suffered isolated equipment damage due to water flooding. The VA Hospital did not suffer any equipment damage.

BBA suffered heavy electrical hardware damage in the flooded segments of floors, along with many heating, ventilation, and air conditioning (HVAC) and mechanical fixtures with moderate damage due to rigid connections in the mechanical room. These included heat-exchanger union connection failure, leading to a massive glycol leak, rigid-water-pipe connection failure, air-duct connection failure, and damage of pipes due to collision with a system in a different plane (Figures 7.19 and 7.23). All lighting units were destroyed in the penthouse mechanical room. A sprinkler was damaged in the mechanical room because of hitting an air unit. Cast-iron-roof drainpipes were damaged or disconnected, allowing runoff water into the penthouse. Variable-air-volume units in four different locations on the second floor, the radiator segments of the heating systems, had splits in the pipe, leading to water venting onto the drop ceiling and then the floor. These were isolated by using valves as they were discovered, but water was vented, causing damage to ceiling tiles, drywall, and several pieces of computing equipment and phones. Several components of the fire suppression systems were damaged because of water leaking throughout the building. Because of water runoff, two fan motors were damaged in the “walk-in blood-storage freezer” as a result of water infiltration and subsequent freezing, which caused them to fail. One concern BBA staff expressed was that many systems did not restore service efficiently after the initial assessment that they had no damage.



(a)



(b)



(c)



(d)

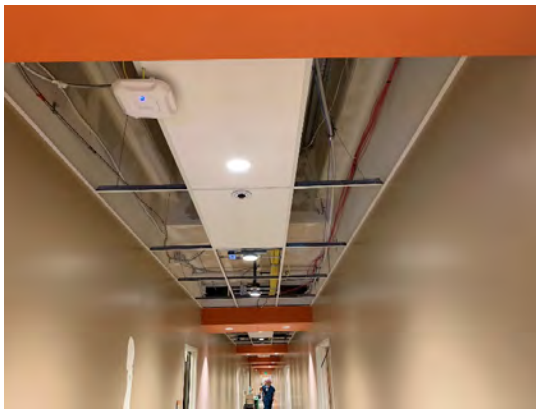
Figure 7.23. Glycol pipe (a) connection failure and (b) leak at BBA mechanical room, (c) air-duct connection damage at BBA's second floor, and (d) pipe connection failure at the BBA mechanical room (photos: BBA).

Some elevators were out of service in the three Anchorage hospitals for various reasons, such as seismic sensor shut-off, water leakage, or counterweight damage or dislocation. In the case of Patient Tower D in PAMC, the water leak caused one elevator to malfunction with two people inside, and these individuals were rescued after the earthquake. The water leak through that elevator went as far as the ground level. The other elevators in Tower D were out of service because of counterweight problems. Elevators of Parking Structures 2 and 4 at PAMC also suffered counterweight damage. In one of Anchorage's hospitals, an unrestrained heavy mechanical unit slid a few inches, causing pipe damage (Figure 7.22).

The PAMC Mat-Su Valley imaging facility suffered moderate damage that included coils, glycol heating lines, gas system and rooftop chillers, and HVAC units. The PAMC Eagle River facility had imaging equipment (CT-scanner and X-ray equipment) that did not get affected by the severe water flooding that occurred in the facility. In addition, that facility suffered mechanical, HVAC, and flooring nonstructural damage.

7.3.3 Ceiling, Walls, and Other Nonstructural Damage

At Mat-Su Regional's urgent care clinic in Wasilla, ceiling tiles fell, and gypsum wallboard cracked. Figures 7.24, 7.25, 7.26, 7.27, and 7.28 show sample ceiling and wall damage from Anchorage hospitals. Ceiling tile and grid damage due to shaking was common at many hospital campus buildings. Ceiling tile damage due to water flooding and glycol leaks was evident in hospitals in Anchorage and in the BBA. For example, the BBA lost nearly 600 ceiling tiles, primarily because of water and glycol flooding. Sprinkler-head shearing and damage to ceiling tiles was widespread in this earthquake in nearly all hospital buildings (Figures 7.24 and 7.26). Significant cracking in stairwell drywall was very common in all hospital buildings in Anchorage (Figure 7.27). Vertical, horizontal, and diagonal cracking in sheetrock and cracking around openings was also widespread. Thousands of cracks could be traced in one hospital building. The cost of repairing these cracks could be significant because of the large number and the need for scaffolding in many cases of high bays. In an actively seismic region like Alaska, the use of brittle drywall/sheetrock finishes may need to be revisited.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 7.24. Patient building ceiling damage in the (a) hallway and (b) clinic due to water flooding in an Anchorage hospital, (c) office-space ceiling damage due to water in an Anchorage hospital, (d) sprinkler-head damage and ceiling tile damage in patient building (photos: Wael Hassan), (e) drop-ceiling damage at PAMC PS1 (photo: PAMC), and (f) heavy ceiling tile damage at an Anchorage hospital (photo: Wael Hassan).



Figure 7.25. Laboratory ceiling damage due to water flooding at BBA (photos: BBA).



(a)



(b)



(e)



(d)



(e)

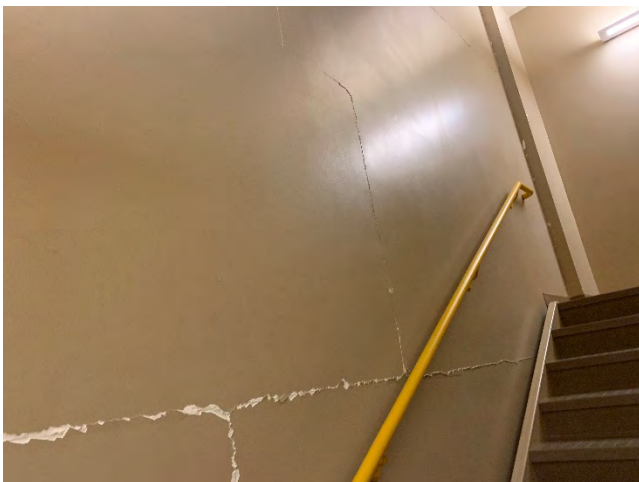
Figure 7.26. (a) Sprinkler head–damaged drop ceiling at PAMC Sky Bridge, (b) floor damage due to ground failure at an Anchorage hospital, (c) typical sheetrock wall damage in all three Anchorage hospitals, (d) ceiling grid failure, and (e) typical diagonal wall crack around openings (photos: Wael Hassan).



(a)



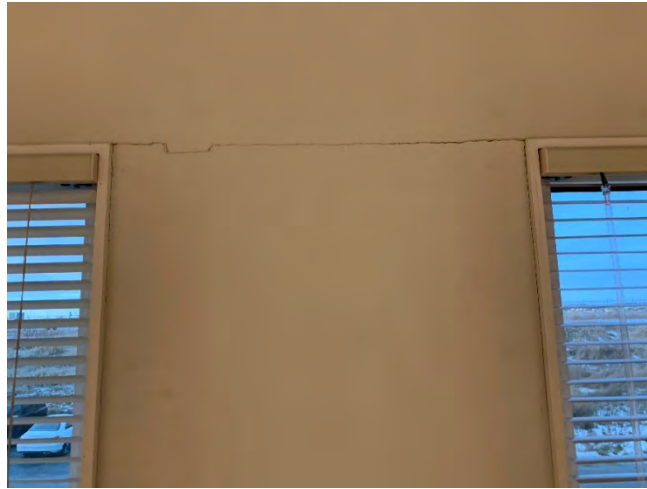
(b)



(c)



(d)



(e)

Figure 7.27. (a–d) Typical stairwell sheetrock damage in Anchorage hospitals, which was common in all hospital and office buildings, and (e) typical wall panel crack (photos: Wael Hassan).

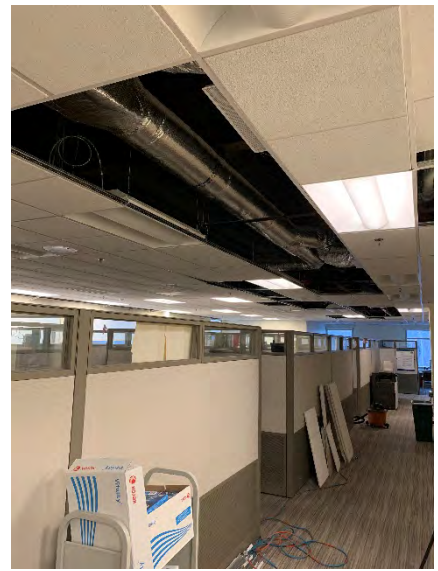
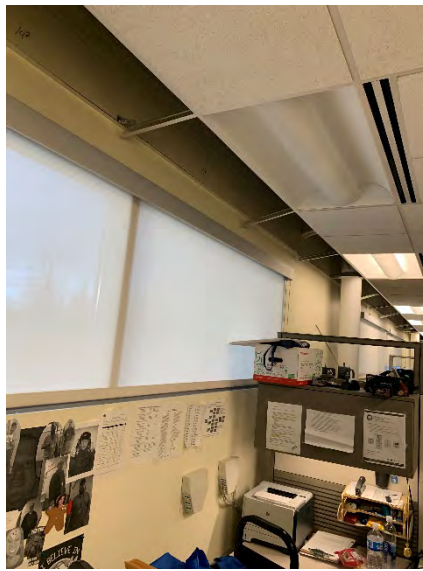


Figure 7.28. VA Hospital in Anchorage, nonstructural ceiling damage (photos: Erol Kalkan).

Floor damage due to soil failure occurred at some locations in one of the hospitals in Anchorage. Many door jams and window mechanical systems were damaged because of permanent deformations (Figure 7.29).



Figure 7.29. Examples of (a) door jamming and (b) window system failure in Anchorage hospitals (photos: Wael Hassan).

7.4 Hospital Response and Preparedness

Immediately after the earthquake, Mat-Su Regional Medical Center activated their hospital emergency operations center and announced a “Code Black,” which requested personnel across the health system from their labor pool, including in private clinics and practices, to report to the hospital to respond to a possible surge of patients with earthquake-related injuries. There were about 120 people seen at Mat-Su Regional related to the earthquake, in addition to 80 patients who were deemed regular ER patients. The hospital was able to accommodate these new cases without discharging existing patients. There were no building collapses and few instances of major structural damage, all of which limited the number of injuries to a number that the hospital was able to manage.

Only 2 weeks prior to the event, the hospital held a full-scale drill with a major earthquake as the scenario, in which the road to Anchorage was closed, water and gas leaks occurred, and multiple utilities and computer systems were down. As a result, emergency procedures were “fresh in everyone’s mind” according to a clinic manager interviewed. After the drill, staff members evaluated their workspaces and identified the safest places to take cover during an earthquake. In the real November 30 event, staff members were able to take cover quickly and cover or protect patients (Cahill, 2019).¹

Mat-Su Regional’s Wasilla and Knik urgent care clinics closed for the day because of nonstructural damage in Wasilla, loss of power in Knik, and a lack of staff, who had redeployed to the hospital in response to the Code Black. At the Wasilla location, the fire alarm went off, causing occupants to evacuate the building. The backup generator came on and functioned when power went out. The Knik location lost power until about 3 p.m. on the day of the earthquake, and an ice machine slid and came off its feet. In Palmer, mechanical systems needed a reset after the earthquake, but the clinic did not suffer other significant damage. It was set up as an off-site location for the “walking wounded” under the hospital’s emergency plan, with staff coming from other facilities. The anticipated patient surge at the off-site location did not materialize, primarily because shaking was modest. A structural engineer inspected all facilities for damage.

PAMC underwent several seismic-upgrade projects on many buildings prior to the earthquake. Main PAMC Anchorage campus Tower D, built in 1960, was upgraded twice in 1986 and 1994. Patient Building F, built in 1973, and building B, built in 1971, were also upgraded prior to the earthquake. Several parking structures were upgraded and FRP-retrofitted at various stages before 2018. An addition and upgrade to Providence Regional Building, built in 1961, also took place prior to the event. Most of the other buildings on the Anchorage campus were built after 1983 and did not need a major upgrade. For example, Patient Buildings G and H (constructed in 1984) and new ER Building E (constructed in 2000) needed only insignificant renovation prior to the earthquake.

Earthquake drills take place bimonthly on average at PAMC. Building managers seem to have some emergency-response plan, in coordination with the hospital’s emergency-response team, but the general employee population does not seem to have emergency-response instructions or lead-person written or known procedures. Tsunami evacuation plans were not present at PAMC, perhaps because of the low risk associated with Cook Inlet configurations.

According to NEESER Construction Inc., ARH Office Building W (three stories, 50,000 sq. ft.) and Building C (four stories, 88,000 sq. ft) were renovated at a cost of \$24 million. Alaska Regional Pipe Rehab is a major project of 500,000 sq. ft. to upgrade the hospital's building systems, in which the water piping system was completely upgraded, along with associated interior finishes and retrofits to allow access to pipes. Alaska Regional was the hospital that had the most damage. The ARH staff's response to control chaos and calm patients was remarkable (ARH staff, *pers. comm.*, 2018). No information is available on post-earthquake emergency plans at Alaska Regional or ANMC.

At the time of this report, the BBA still does not seem to have written procedures for personnel for the emergency response following a major earthquake event.

7.5 Hospital Resilience and Cost of Repair

7.5.1 Hospital Resilience

The hospital resilience was generally good following the earthquake, with all ERs operational immediately following the event, except for one with major flooding that prompted establishing a makeshift replacement until repairs can be performed. So an estimated resilience of ERs closer to 100% could be cited. The remaining hospital service operations were affected differently at different hospitals/buildings as presented next.

PAMC in Anchorage was approximately 100% resilient following the event because no official shutdown of any part of the Anchorage campus took place, including ERs. Mercifully, at the time of the earthquake at 8:29 a.m., there was no single surgery under way, which is contrary to the daily norm at that time of the day. However, PAMC cancelled all elective surgeries the day of the earthquake, pending further damage assessment. Even with water flooding of a major hallway of the fourth floor of Main Tower D, the main patient building, no disruption of operations took place, as the building managers found alternate means to keep that level operational. However, one elevator that went out of service because of flooding and other elevators that went out of service because of counterweight problems dictated using the stairs for a few hours as the primary vertical transportation means.

ARH cancelled all elective surgeries and noncritical appointments and limited services to the ER. The hospital campus experienced major water flooding at several locations. This affected large segments of floors and ceilings because of firefighting system failure that led to shutting down two outpatient clinic buildings, B and C, on campus. The repairs of these two buildings included major water drying and electrical wiring repairs and replacements due to flooding and nonstructural damage, which dictated moving radiology units to off-campus sites. The main building remained operational for ER services only, despite some minor-to-moderate structural cracks and moderate nonstructural damage. The main buildings of the hospital resumed full operations on Monday, December 2. The outpatient clinic buildings, B and C, partially resumed operation with an estimated 20%–30% capacity 2 weeks after the earthquake.

The BBA was shut down for donations for 1 day following the earthquake. However, during that day, personnel were still able to transport blood supply to hospitals. It is noteworthy that the BBA blood-collection system dictates sending daily supply to hospitals with little blood stock to remain in the BBA building. Upon resuming operations 1 day later, it was found that several building systems initially assessed with no damage, including some heating and ventilation subsystems, were not operational because of hidden damage that required further inspection and repair. Thus, full functionality was still not reached a few days following the event. At the time of this report, major concrete crushing at the penthouse stairs had not been repaired. Several heating mechanical systems were still using temporary repairs, pending federal assistance to complete permanent repairs.

7.5.2 Hospital Cost of Repair

The relatively good performance of PAMC reflected positively on the cost of earthquake-damage repair. The total repair cost is about \$1.2 million, covering the entire Anchorage campus, Eagle River outpatient locations, and several Mat-Su Valley outpatient and imaging facilities. This is considered a relatively small cost, given the size of the event and the PAMC facilities. It is instructive to look at some breakdowns of this cost. The PAMC Anchorage campus cost of repair is about \$663,000 (the campus is 2 million sq. ft.), while the main PAMC Anchorage patient buildings' cost of repair is about \$444,000 (Buildings D, E, F, G, E, and H). The cost of repair for water-related damage and mechanical damage in Main Tower D is \$254,000, while that of Patient Building F is about \$133,000. It is worth mentioning, however, that the relatively good performance of the main campus in Anchorage should be viewed in light of the structural system of most buildings,

which is composed of flexible steel-moment frames; the small intensity of the ground shaking in the regions (about 0.21g); and the relatively young age of most patient buildings and the retrofitting projects of older ones.

The cost of repair for off-campus PAMC locations in Eagle River and Mat-Su Valley is about \$540,000, which is considered relatively high, considering the size and equipment of the off-campus clinics. This observation is in line with heavier nonstructural damage in Eagle River locations. The off-campus Eagle River locations did not suffer damage to CT or X-ray equipment; however, several private clinics without the office buildings of these locations suffered water and nonstructural damage and needed to suspend services to patients and direct them to alternate locations. An example was a pediatrics practice in the PAMC Eagle River office building that directed all its patients to its PAMC Anchorage campus, which created severe demand on the latter.

The cost of repair of ARH was not available at the time of the preparation of this report. However, given the extent of damage, it is expected to be higher than that of PAMC, despite its smaller square footage. The cost of repairs at ANMC and Mat-Su Regional was not available at the time of this report.

The BBA's cost of structural repairs is about \$17,000, primarily to fix the concrete stairwell. The overall cost of repairing mechanical equipment, water damage, and ceiling and sheetrock damage is estimated to be \$65,000.

7.6 Earthquake Preparedness Needs

At the time of this report, follow-up hospital-impact surveys still needed to be performed to capture lessons from the health system's response to the earthquake. Furthermore, epidemiology studies investigating causes of injuries would be a valuable addition to existing studies from past earthquakes on injuries, protective actions taken during earthquakes, and interior environments.

At the time of this report, interviewing hospital personnel does not imply the presence of fully functioning post-earthquake response plans that include detailed written procedures on the roles of each employee or the lead person, an approach followed in many other seismically prone regions. The example of Chilean hospitals' earthquake and tsunami response procedure is recommended for Alaskan hospitals.

Backup communication plans that assume total loss of telecommunication networks do not seem to be in place in all three major hospitals in Anchorage. These backup plans are much needed to coordinate patient and emergency supply transports among the three major hospitals and to coordinate locating and transporting health care professionals among the three hospitals. Alternative communication means, including off-line mobile apps, emergency satellite phones, and long-range radio communications are recommended for such plans for Alaskan hospitals.

Because the Mat-Su Regional Medical Center does not enjoy redundancy within its vicinity, post-earthquake communication and patient and medical supply transport plans should be in place, assuming collapse of several segments of the only artery that connects Mat-Su Valley to Anchorage hospitals, the Glenn Highway. These plans should consider air ambulance scenarios and capacities. Similar scenarios should be investigated for Eagle River and the Northern Communities, which have especially high vulnerability to serious injuries and fatalities following a major event, with the possibility of collapsed portion(s) of the Glenn Highway, their only route to Anchorage.

It is noteworthy that all of the above-recommended hospital response plans should consider severe, snowy weather conditions in the winter season between December and February. The readers are referred to the National Institute of Standards and Technology special publication 1224, *Research Needs to Support Immediate Occupancy Building Performance Objective following Natural Hazard Events* (Sattar et al., 2018),² for further details regarding performance of hospitals in major earthquake events. The readers are also encouraged to consult the 2013 Oregon Resilience Plan (Oregon Seismic Safety Policy Advisory Commission, 2013),³ several Federal Emergency Management Agency hospital earthquake safety guides (e.g., FEMA, 2007),⁴ and California Office of Statewide Health Planning and Development guides.

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- ¹ Cahill, K., 2019. Mat-Su Regional earthquake preparedness and response, One Year Later: Alaska Earthquake Symposium, September 24–26, 2019, Anchorage, AK.
- ² Sattar, S., T. McAllister, K. Johnson, C. Clavin, C. Segura, S. McCabe, J. Fung, L. Abrahams, E. Sylak-Glassman, M. Levitan, K. Harrison, and J. Harris, 2018. Research Needs to Support Immediate Occupancy Building Performance Objective following Natural Hazard Events, available at <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1224.pdf> (accessed April 2020).
- ³ Oregon Seismic Safety Policy Advisory Commission (OSSPAC), 2013. The Oregon resilience plan: reducing risk and improving recovery for the next Cascadia earthquake and tsunami, available at https://www.oregon.gov/oem/Documents/Oregon_Resilience_Plan_Final.pdf (accessed April 2020).
- ⁴ Federal Emergency Management Agency (FEMA), 2007. Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds, FEMA 577.

8 IMPACT ON TRANSPORTATION SYSTEM

8.1 Transportation System in Southcentral Alaska

The state of Alaska transportation system (Figure 8.1) includes 1,592 bridges and 50 highways, besides hundreds of municipal roads. The earthquake-affected region (Metropolitan Anchorage) in Southcentral Alaska includes 245 bridges.

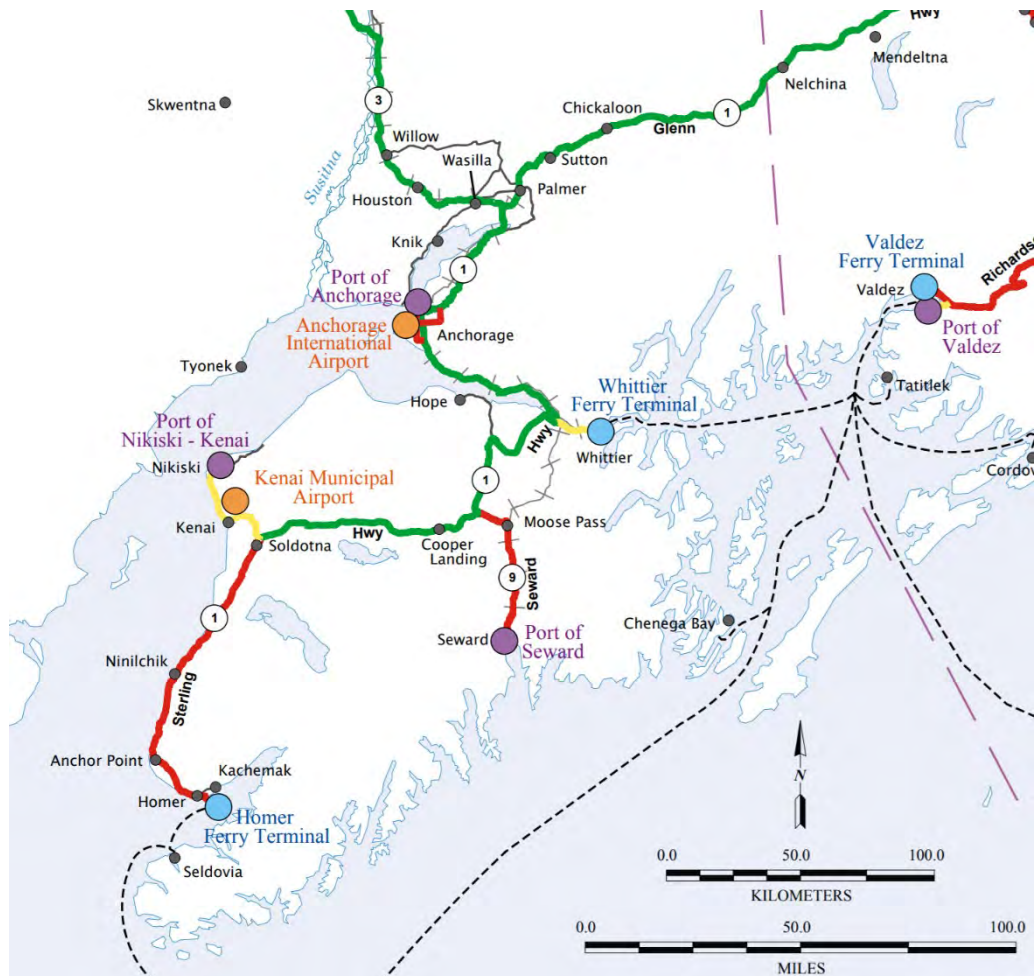


Figure 8.1. National and Interstate Highway System in Southcentral Alaska (source: Alaska Department of Transportation and Public Facilities).

The 2018 Federal Highway Administration (FHWA) National Bridge Inventory (NBI) classifies 9.7% (155 bridges) of the state's bridge inventory as structurally deficient (FHWA, 2018).¹ Twelve of the deficient bridges are on the Interstate Highway System. Prior to the November 2018 earthquake, the state identified 306 bridges needing retrofitting/upgrading at a cost of \$148.7 million. In September 2019, the U.S. Department of Transportation (DOT) assigned \$24.7 million to Alaska for road and bridge repairs, about 40% of which will be used for earthquake-related repairs. Of the deficient bridges, five aging bridges (older than 50 years) are located in the Anchorage Metropolitan Area and are considered heavily traveled (Table 8.1). The Alaska DOT and Public Facilities (ADOT&PF) is actively improving the region's road and bridge infrastructure and building new seismically resistant bridges in Southcentral Alaska because of increased population demand.

Table 8.1. Top most-traveled structurally deficient bridges in Alaska (source: FHWA, 2019).

County	Year Built	Daily Crossings	Type of Bridge	Location
Ketchikan Gateway	1957	15,147	Urban minor arterial	South Tongass Highway over Hoadley Creek
Ketchikan Gateway	1955	12,481	Urban minor arterial	South Tongass Highway over Water Street Viaduct
Fairbanks North Star	1953	8,593	Urban minor arterial	Wendell Avenue over Chena River (Wendell)
Anchorage	1966	6,768	Rural Interstate	Seward Highway over Portage Creek No. 1
Ketchikan Gateway	1975	6,277	Urban minor arterial	North Tongass Highway over Ward Creek
Fairbanks North Star	1953	5,325	Urban minor arterial	Minnie Street over Noyes Slough (Minniet Street)
Anchorage	1966	5,205	Rural Interstate	Seward Highway over Virgin Creek
Anchorage	1966	5,205	Rural Interstate	Seward Highway over Glacier Creek
Anchorage	1967	5,205	Rural Interstate	Seward Highway over Twenty Mile River
Anchorage	1966	5,205	Rural Interstate	Seward Highway over Peterson Creek

8.2 Observed Bridge Damage

The observed structural damage to the region's inventory of 245 bridges was generally minor, with 20 bridges identified by the ADOT&PF to have more significant structural damage needing permanent repairs to be conducted in 2020. The ADOT&PF inspection teams inspected 243 bridges in 5 days following the earthquake, bounding the inspections to regions with 0.2g peak ground acceleration or higher (Figures 8.2 and 8.3). The Earthquake Engineering Research Institute (EERI) Field Reconnaissance Team inspected only five bridges in the first few days following the earthquake on the Glenn Highway. Most of the structural damage observed was related to soil failure.



Figure 8.2. The new Glenn Highway–Muldoon Road Interchange in Anchorage (opened in 2017) (source: ADOT&PF).

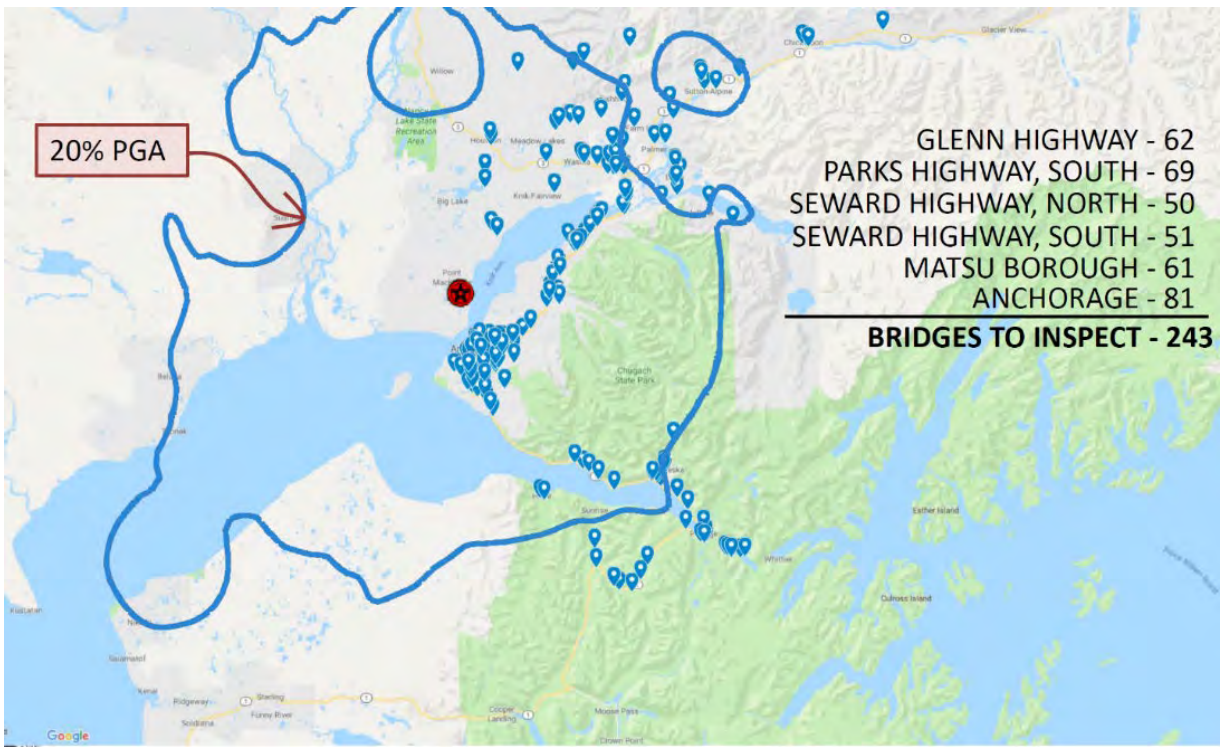


Figure 8.3. Inspection area of ADOT&PF inspection teams (source: Nick Murray).

Structural damage commonly found was girder shifting, shear key cracking, light-to-severe cover spalling, and damage of shear keys exposing reinforcement, bent anchor bolts, bearing large deformation, damage of grout pads under bearings, pile-cap concrete spalling, wing and hider wall cracks, and bridge transverse and longitudinal permanent displacement and misalignment. Figures 8.4, 8.5, 8.6, 8.7, 8.8, 8.9, 8.10, 8.11, 8.12, and 8.13 depict examples of common structural and soil damage observed in bridges.

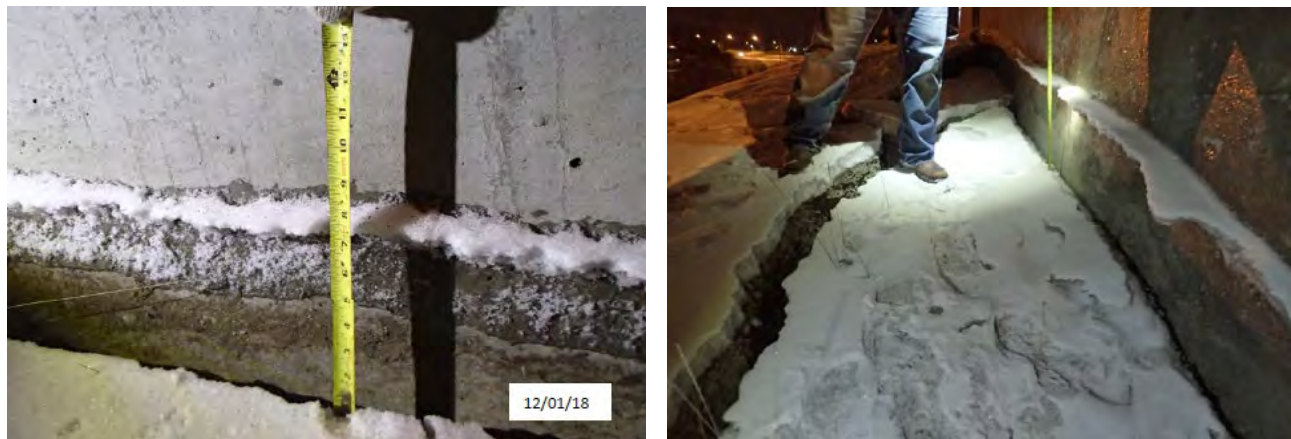


Figure 8.4. A 16-inch wing wall settlement of a bridge (photos: Nick Murray and Ben Still).



(a)



(b)



(c)

Figure 8.5. (a) Anchor-bolt bending and (b, c) grout-pad splitting and damage (photos: Nick Murray and Ben Still).



(a)



(b)

Figure 8.6. (a) Wing wall cracks (photo: Nick Murray and Ben Still) and (b) concrete-embankment-panel settlement (photo: Sara Manning and Ben Fetterhoff).



Figure 8.7. Hider wall cracks (photos: Nick Murray and Ben Still).



(a)



(b)

Figure 8.8. (a) Abutment cracking (photo: Jesse Escamilla and Ben Fetterhoff) and (b) cracked concrete sloped panels (photo: Sara Manning and Fred Paulsen).



Figure 8.9. Shear key damage (photos: ADOT&PF).



Figure 8.10. Spalling at pile pier cap (photo: Sara Manning and Fred Paulsen).



Figure 8.11. Culvert damage (photo: Jesse Escamilla and Ben Fetterhoff).



(a)



(b)

Figure 8.12. (a) A 2.5-inch lateral displacement of a bridge (photo: Nick Murray and Ben Still) and (b) diaphragm longitudinal displacement (photo: Jesse Escamilla and Ben Fetterhoff).

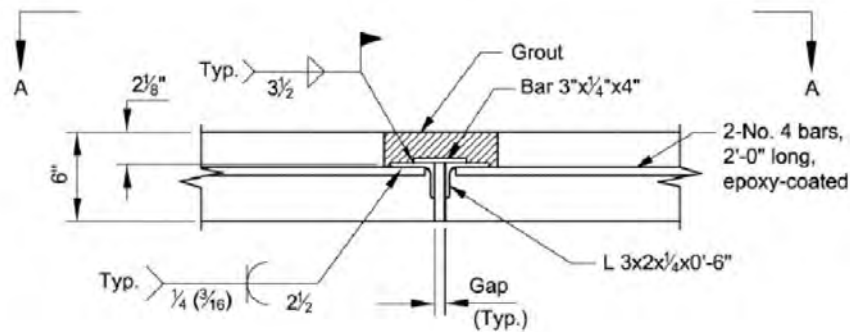
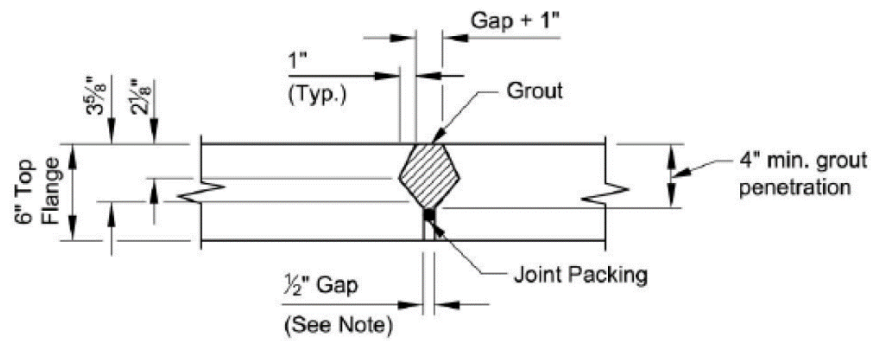


Figure 8.13. Wing wall 1.5-inch displacement for 20 feet (photo: Nick Murray and Ben Still).

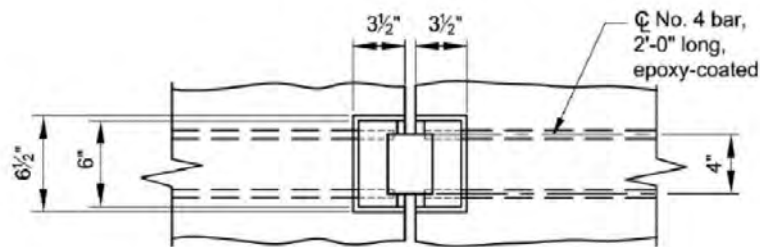
Structural damage due to ground failure was common. This was manifested in abutment cracks (hairline to about 0.5 inches wide), approach settlement, settlement of abutments, wing wall settlement, soil cracks, hider wall cracks, culvert failure, rail misalignment, and slope tension cracks. In one incident, damage to a corrugated-metal-pipe pedestrian undercrossing was caused by waterline breakage. Settlement of soil was common and reached 16 inches in one case (Figure 8.4).

The ADOT&PF bridges' fundamental periods range from 1.5 to 3.5 seconds. Recorded ground acceleration was about 30% of the design earthquake acceleration for this period range, and all bridges responded elastically with minor structural damage, in many cases related to soil failure. The 20 bridges that had more significant damage mostly suffered shear key, connector, and abutment damage. Shear keys are expected to have damage in strong shaking (Figure 8.14). Bridge closures were due to approach road failure, not structural damage to the bridge. The ADOT&PF provided a list of bridge damage, shown partially here as:

- cracking in 6 Mile Bridge, Seward,
- a cracked girder on the east side of Rabbit Creek Bridge,
- cracking on both sides of Diamond Bridge,
- abutment cracking on both sides of Tudor Bridge,
- north-base end cracking on O'Malley Bridge,
- abutment damage and slope failure on northbound Eagle River Bridge,
- residual vertical displacement on southbound Eagle River Bridge,
- vertical displacement at joint on Kings River Bridge,
- cracking at headwall on Chickaloon Bridge,
- minor cracking in Purinton Creek Bridge,
- cracking in retaining wall in Bragaw Bridge,
- cracking in Seward Meridian Bridge,
- cracking in the bridge at mile point 82 on Sterling Highway,
- cracking in Minnesota Bridge at 100th,
- damage to Biggs Bridge pedestrian undercrossing due to a broken water main, and
- damage to Biggs Bridge southbound expansion joint on both sides and to the north abutment.



Shear Connector Detail



View A-A

Figure 8.14. Typical ADOT&PF shear key and shear connector details (source: ADOT&PF Bridge Manual²).

8.3 Observed Road Damage

Significant widespread damage to highway roads resulted from the earthquake (Figure 8.15). ADOT&PF reported 58 locations of damage on the road system in the region, with 8 locations identified to have the most damage. The EERI team inspected the road damage at 10 locations of the most affected roads. The full description of road damage along with the repair time is reported in the next section. Geotechnical Extreme Event Reconnaissance (GEER) (Franke and Koehler, 2019)³, and Thornley et al. (2019)⁴ identify locations of road damage in Figures 8.16 and 8.17.

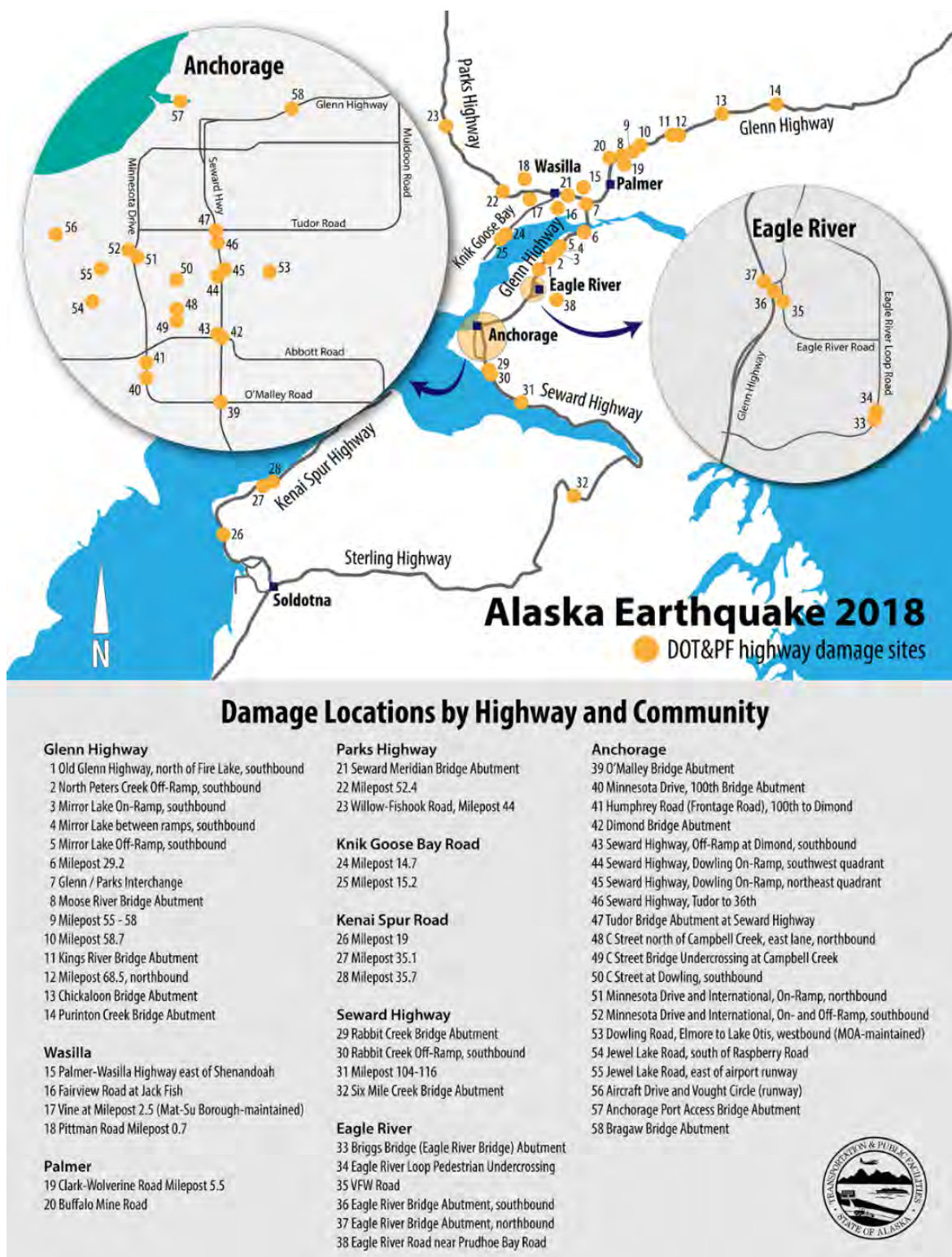


Figure 8.15. Earthquake damage locations in roads and bridges (ADOT&PF).

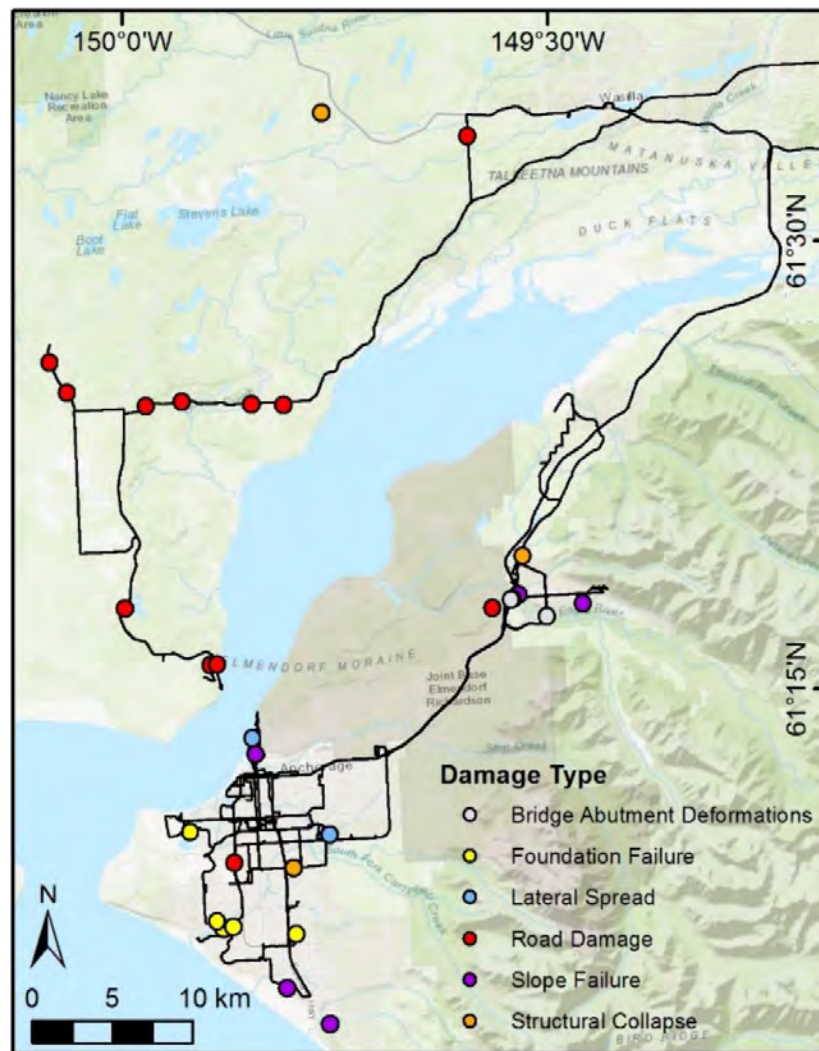


Figure 8.16. Earthquake road damage locations identified by GEER (Franke and Koehler, 2019).

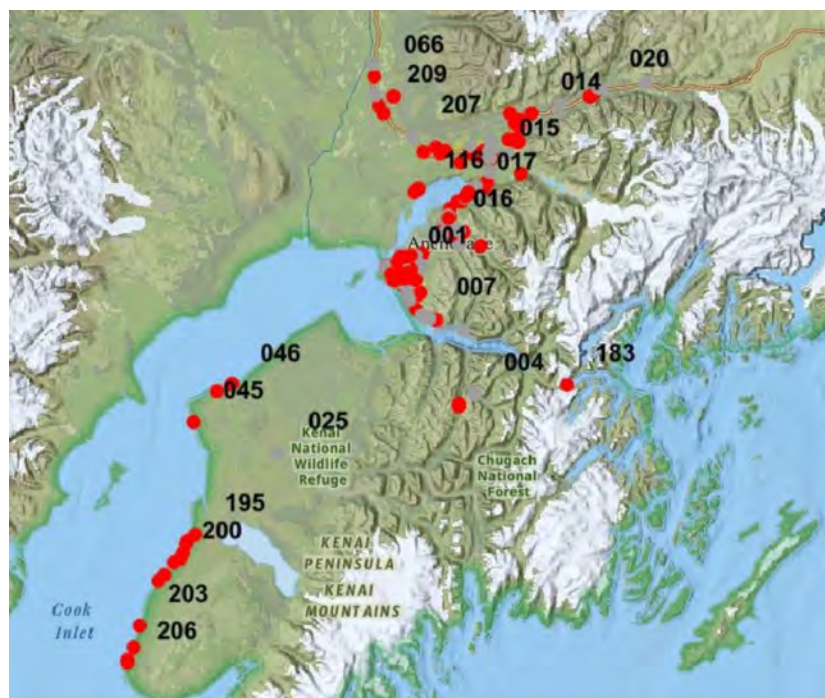


Figure 8.17. Earthquake road damage locations identified by Thornley (2019).

Liquefaction-induced settlement of roadways was not common but did occur in parts of Anchorage and outlying areas. An example of the damage resulting from liquefaction included portions of the Seward Highway north of East Tudor Road. Both the northbound and southbound lanes settled differentially by several inches and were closed to traffic for safety. In the days following the earthquake, the ADOT&PF was able to work with a contractor to remove distressed pavement, level the subgrade, and repave the affected lanes as a temporary measure. Additional repairs will be performed for a permanent repair, as the affected area continued to settle after the spring thaw and still has uneven driving lanes.

Several significant slope failures occurred as a result of the earthquake. Observations following the November event indicated that major slope failures from the 1964 Great Alaska Earthquake did not remobilize (Rob Witter, USGS, *Randall et al.*⁶). The relatively short duration of shaking, when compared to the 1964 earthquake, is thought to be one reason these slopes did not remobilize. However, several other slope failures were observed and documented. Notable slope failures included the slopes near milepost 50 of the Seward Highway (Figure 8.18), milepost 24 on the Glenn Highway near Mirror Lake (Figure 8.19), and slopes near the Alaska Railroad Corporation tracks near Rabbit Creek in South Anchorage (Franke and Koehler, 2019).



Figure 8.18. Seward Highway milepost 50 damage (source: Thornley, 2019).



Figure 8.19. Damage to Glenn Highway at Mirror Lake (source: Thornley, 2019).

At the time of the earthquake, there were about 0.3–0.5 m of seasonally frozen ground, which can behave as a stiff crust over the thawed soils below. In the months following the earthquake, observations along road embankments have found cracks parallel to the crest of embankment slopes, which in many cases are in line with guardrails. The cracks in the embankment are typically at the edge of the pavement and range from less than an inch to several inches wide, with depths of 0.3 m to up to 1 m in some cases. Many of these cracked embankments do not show vertical displacement and are primarily horizontal. In some instances, the near-surface slides damaged culverts.

As spring thawed out the frozen soils, there were several embankments that slumped, causing pavement damage and roadway settlement. These damages, while occurring several months after the earthquake, are attributed to frozen soils that lose the bridging effect once thawed.

Some of the larger failures that were observed consisted of native foundation soils that failed below fill soils. Two examples of this, which received national and international attention in the days following the earthquake, include Vine Road in Wasilla and the Minnesota Drive northbound off-ramp at International Airport Road in Anchorage (Figures 8.20 and 8.21). Both sites included constructed road embankments over soft soils. While both sites are being studied to understand the failure mechanisms, it appears that in both cases, the foundation soils failed and caused rotational failures of the overlying embankments.



Figure 8.20. Vine Road earthquake damage (photo: EERI Clearinghouse).



(a)



(b)

Figure 8.21. Northbound Minnesota at International Airport Road: (a) earthquake damage and (b) after repair. (source: Thornley, 2019).

The Minnesota Drive off-ramp is constructed in an area where groundwater is near the surface and peat soils overlie fine-grained sandy silt, which tends to be soft near the ground surface (Schmoll and Dobrovolsky, 1972). The initial failure mode is assumed to be global rotational slope failure due to low-shear-strength, saturated, sandy silt soils unable to resist the driving forces of the roadway embankment fill above.

Because of the glacial terrain comprising ridges of glacial till consisting of silt, sand, and gravel and valleys with deep peat or muskeg found across Southcentral Alaska, road construction can be challenging. The muskeg is often found to be greater than 3 m deep, and surcharging is a common practice in lieu of overexcavation. Vine Road, at the location of the

failure, crosses deep muskeg. Observations suggest that the failure is again likely due to global rotational slope failure caused by saturated low-shear-strength peats supporting the road embankment. This site will be interesting for further study because there are numerous roads that were constructed in similar conditions that did not fail because of the Anchorage earthquake.

8.4 Road System Repairs and Resilience

The map in Figure 8.15 shows damage sites identified by the ADOT&PF. The total damage sites included 58 sites. There were 20 damage sites in Anchorage, 6 in Eagle River, 4 on Seward Highway, 3 on Kenai Spur Road, 2 on Knik Goose Bay Road, 3 on Parks Highway, 2 in Palmer, 4 in Wasilla, and 14 on Glenn Highway. A brief list of damages to bridges was presented in the previous section. The following is a more comprehensive description of the significant reported damage in roads and bridges, with an indication of the timeline for repair (as provided by the ADOT&PF (Figure 8.22)):

- Seward Highway was initially closed at milepost 112 because of a rockslide. As of 1:35 p.m. on the day of the earthquake, Seward Highway was reopened.
- Kenai Spur Highway had a 150-foot-long by 8-inch-wide crack in road at mile points 35.1 and 35.7 and a 500-foot-long by 4-inch-wide crack at mile 19.7. The road remained open, as the damage could be passed with care. Repairs at mile point 19.7 were completed on December 1, and the repairs at mile points 35.1 and 35.7 were completed on December 2. It was reported that permanent repairs would take place in the spring.
- The Glenn Highway northbound Eagle River Bridge closed, but detour through Eagle River was possible. On December 1, two of the three lanes were reopened, while the third lane remained closed for repairs. Speed restrictions remained in place but were lifted on December 6 after further repairs.
- At the Parks/Glenn interchange, there was slope failure that led to closure of the off-ramp to Palmer. On December 2, this was reopened to one lane. Guardrail removal and jersey barrier placement (approximately 200 feet) was completed by December 4.
- There was a rockslide on Richardson Highway, but it remained open.
- Extensive damage, including slope failures, was reported on Glenn Highway between mile points 23 and 25 (Eklutna to Mirror Lake), which led to road closure with one-lane detours in each direction. Passage of long combination vehicles was not deemed practical. Repairs were completed, and the road was reopened on December 5.
- New Seward Highway between Tudor Road and 36th Avenue had buckled pavement, shown in Figure 8.23, leading to closure of two lanes, with one lane remaining open. The road was reopened to three lanes northbound and two lanes southbound on December 4. All work was completed by December 6.
- Biggs Bridge was closed in Eagle River to enable repair of a compromised pedestrian bridge and repair of a broken water main. Repair work was completed on December 6, and the bridge was reopened to traffic on December 7.
- Minnesota Drive northbound and southbound ramps to International Airport Road were closed and repaired, as shown in Figure 8.24. Both were reopened on December 4. The southbound ramp was temporarily closed on December 8 to allow barrier installation.
- Significant damage to Vine Road was caused by liquefaction of soil, as shown in Figure 8.25a. The damage to Vine Road was the most extensive of any road damage caused by the earthquake. Vine road was repaired and reopened on December 8, with a photo of the repaired road provided in Figure 8.25b.
- One lane on Glenn Highway southbound, just south of Knik River at Old Glenn Highway was damaged. Repair of a large shoulder crack was completed on December 4. The outside lane remained closed.
- No structural bridge damage was reported.
- A subsidence (sink hole) at milepost 0.7 on Pittman Road led to the road being reduced to one operational lane.
- Cracks were reported in Seward Meridian Bridge, but the road remained open.
- Two to ten inches of shoulder separation were reported at Fairview Loop at Jackfish, but the road remained open.
- Asphalt jacking occurred at Kings River Bridge on Glenn Highway to address vertical displacement at the joint, but the road remained open.
- There was cracking in the headwall at Chickaloon Bridge on Glenn Highway, but the road remained open.
- Small cracks were reported in the road at Purinton Creek on Glenn Highway, but the road remained open.

- Sunken road conditions led to longitudinal cracks on the shoulder and roadway on Glenn Highway at mile point 68.5 northbound, but the road remained open.
- Longitudinal shoulder cracks were reported on Glenn Highway at mile point 58.7. Repairs were made to the driving surface, but more extensive, permanent repairs were put off until the spring. The road remained open, although one lane was closed.
- A subsidence from slope failure led to damaged pavement and embankments on Clark-Wolverine Road, such that one lane remained open.
- A 3-inch subsidence at Vine and Pittman left one lane open.
- Longitudinal shoulder cracks and guardrail damage were reported on Buffalo Mine Road, but the road remained open.
- Cracks in the road and a sinking center and shoulder were reported on Knik Goose Bay Road at mile point 15.2, but the road remained open.
- A 4-inch subsidence of Knik Goose Bay Road was reported at mile point 14.7, but the road remained open.
- Significant cracking across the highway on Palmer-Wasilla Highway (just east of Shenandoah Drive) was reported, but the road remained open.
- Asphalt cracking was reported on Willow-Fishhook Road, but the road remained open.
- A crack in the road on Seward Meridian Bridge on Parks Highway was reported, but the road remained open.
- Asphalt cracks on Parks Highway northbound at mile point 52.4 were reported, but the road remained open.
- Multiple shoulder failures (including shoulder separation) occurred on Glenn Highway from mile point 55 to mile point 58, leading to closure of one lane. One lane remained open. Repairs were made, but more extensive repairs were left until spring.
- Cracking and settling in the area of Dowling and C Street led to paving but no road closure.
- On Minnesota at 100th and Dimond, there was repair work, but the road remained open.
- The westbound lanes of Dowling Road between Lake Otis Parkway and Elmore Road were repaved and reopened on December 6.
- Cracking occurred in Point Mackenzie Road, as shown in Figure 8.26, and repairs were conducted. The road remained open.

As far as complete road closures, Seward Highway was closed and was reopened on the day of the earthquake. Glenn Highway northbound Eagle River Bridge was closed and was reopened the day after the earthquake. At the Parks/Glenn interchange, there was closure of the off-ramp to Palmer that was reopened to one lane 2 days after the earthquake. Damage to Glenn Highway between mile points 23 and 25 (Eklutna to Mirror Lake) led to closure, with the road reopened 5 days after the earthquake. Biggs Bridge in Eagle River was also closed and reopened seven days after the earthquake. The Minnesota Drive off-ramps to International were reopened 4 days after the earthquake. Vine Road, which suffered significant damage due to geotechnical failures, was reopened 8 days after the earthquake. The resulting timeline for reopening of closed roads is provided in Figure 8.22 as a percentage of the total number of roads closed. Not all of the road closures reflected essential travel routes. The ADOT&PF reported that all essential travel routes were restored by December 5, which was 5 days after the earthquake. The ADOT&PF has been conducting long-term repairs using federal emergency-response funds and state funds. Approximately 150 sites were identified that need permanent repairs, and it is anticipated that this may take multiple years to complete.

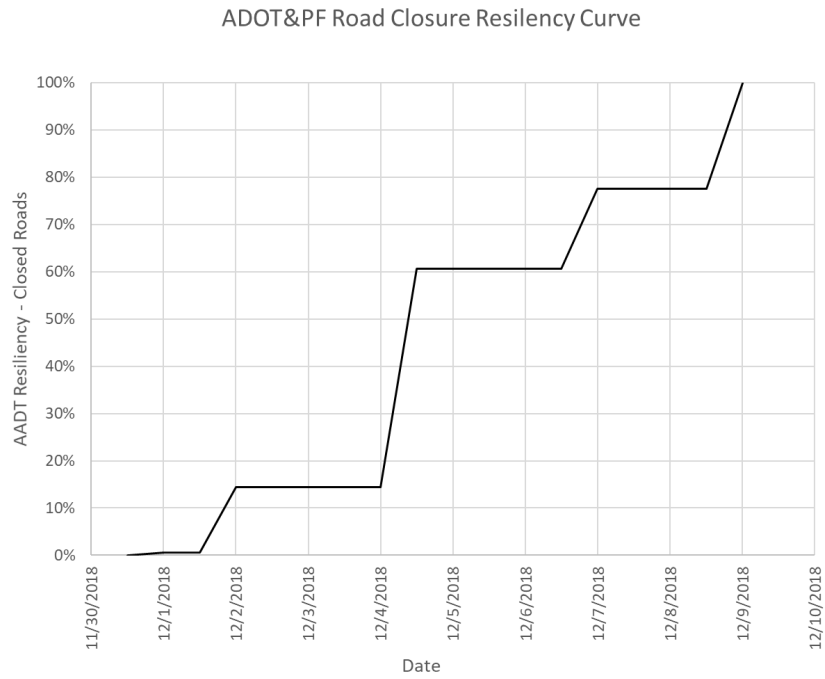


Figure 8.22. ADOT&PF timeline for reopening of earthquake-damaged roads that were closed for repair (ADOT&PF, 2019).



Figure 8.23. Repair of buckled pavement on Seward Highway between 36th Avenue and Tudor Road (photo: Anchorage Daily News).



Figure 8.24. Repair of off-ramp from Minnesota Drive to International Airport Road (photo: Anchorage Daily News).



(a)



(b)

Figure 8.25. (a) Earthquake damage to Vine Road and (b) repaired and reopened Vine Road (photos: KTVA)



Figure 8.26. Damage to Point Mackenzie Road.

8.5 Bridge System Repairs and Resilience

The observed damage did not cause closure of any bridges for structural repair. Some bridges were closed because of road approach failure and reopened as outlined in the previous section. For examples, Eagle River Bridge was closed for a day to repair the roadway, while Biggs Bridge was closed for 7 days to enable repair of a compromised pedestrian bridge and repair of a broken water main.

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9 LIFELINES AND UTILITIES

9.1 Overview

The roads and highways suffered extensive damage because of the earthquake, as presented in the previous chapter. Bridges had minimal structural damage. The railroad suffered moderate damage north of Anchorage, shutting down the railway to Fairbanks. No oil-pipeline damage was reported; however, Trans-Alaska Pipeline System pipelines were briefly shut down for inspections. Widespread interruption of water and power, some 3,000 gas-leakage incidents, and sewer and gas-pipeline failures were reported, affecting thousands of customers. Telecommunications were minimally affected. The postal service worked with reduced capacity because of office damage. These services were swiftly restored within hours to a few days. The Port of Alaska suffered geotechnical failure and widespread infrastructure and pile damage that was only possible to detect following snow melting in spring of 2019. Anchorage International Airport terminals suffered minimum damage, and the airport was operational in 1 hour, with reduced capacity for outbound flights and holding of inbound flights for a few hours.

9.2 Electricity and Power Network

Power outages were widespread within the strongly shaken areas of Anchorage and the Matanuska-Susitna (Mat-Su) Borough immediately following the earthquake. Power was restored quickly following the earthquake, within 24 hours for most customers. Utilities provided outage and service information to the public via outage maps such as Figure 9.1 on their websites starting 2–3 hours after the earthquake and via social media and traditional broadcast and print media.

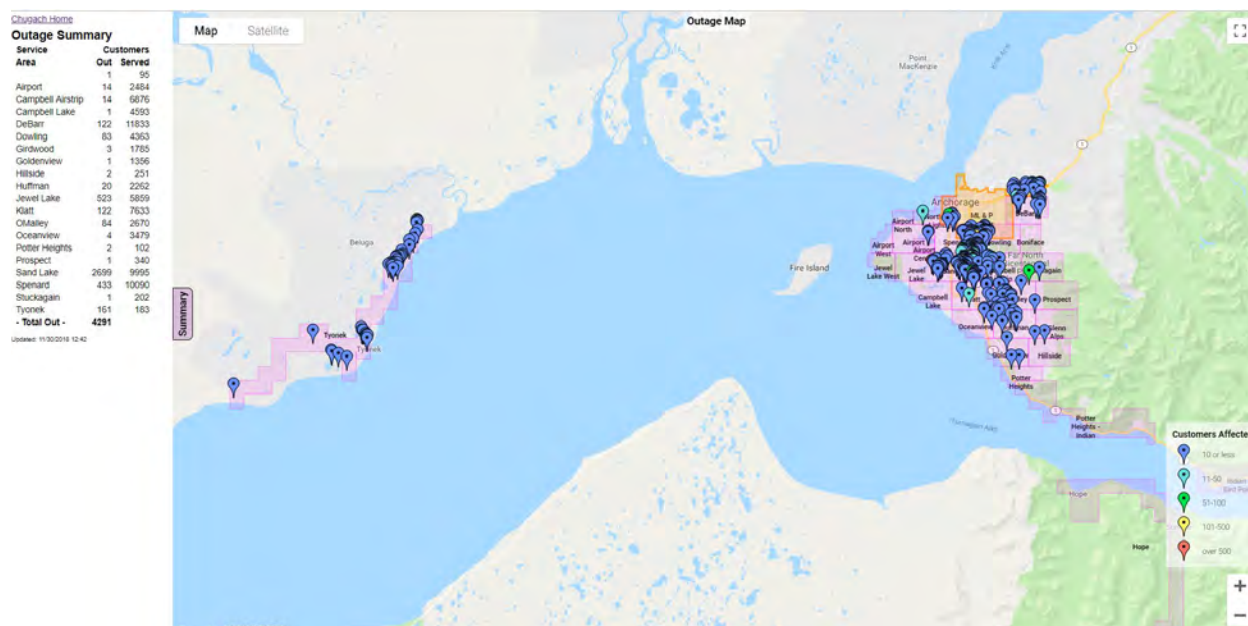


Figure 9.1. Chugach Electric outage map showing 4,291 customers without service at 12:42 p.m. on November 30, 2018. Utilities provided information to the public using maps like these (source: Wael Hassan).

The electric utilities serving the earthquake-affected areas are Municipal Light and Power (ML&P) and Chugach Electric Association in Anchorage and Matanuska Electric Association (MEA) in the Matanuska and Susitna valleys and Eagle River/Chugiak areas. ML&P serves some of Anchorage's oldest neighborhoods. Chugach Electric also serves the Tyonek and Beluga areas on the west side of Cook Inlet, as well as Girdwood, Whittier, and Hope, southeast of Anchorage. On December 4, the Anchorage Assembly voted to approve the sale of ML&P to Chugach Electric, and the proposal sale was in the state's regulatory approvals process at the time of this report. This sale was unrelated to the earthquake and will consolidate Anchorage Bowl electric service under one provider. Figure 9.2 shows service areas for Chugach Electric and ML&P, and Figure 9.3 shows the MEA service area.

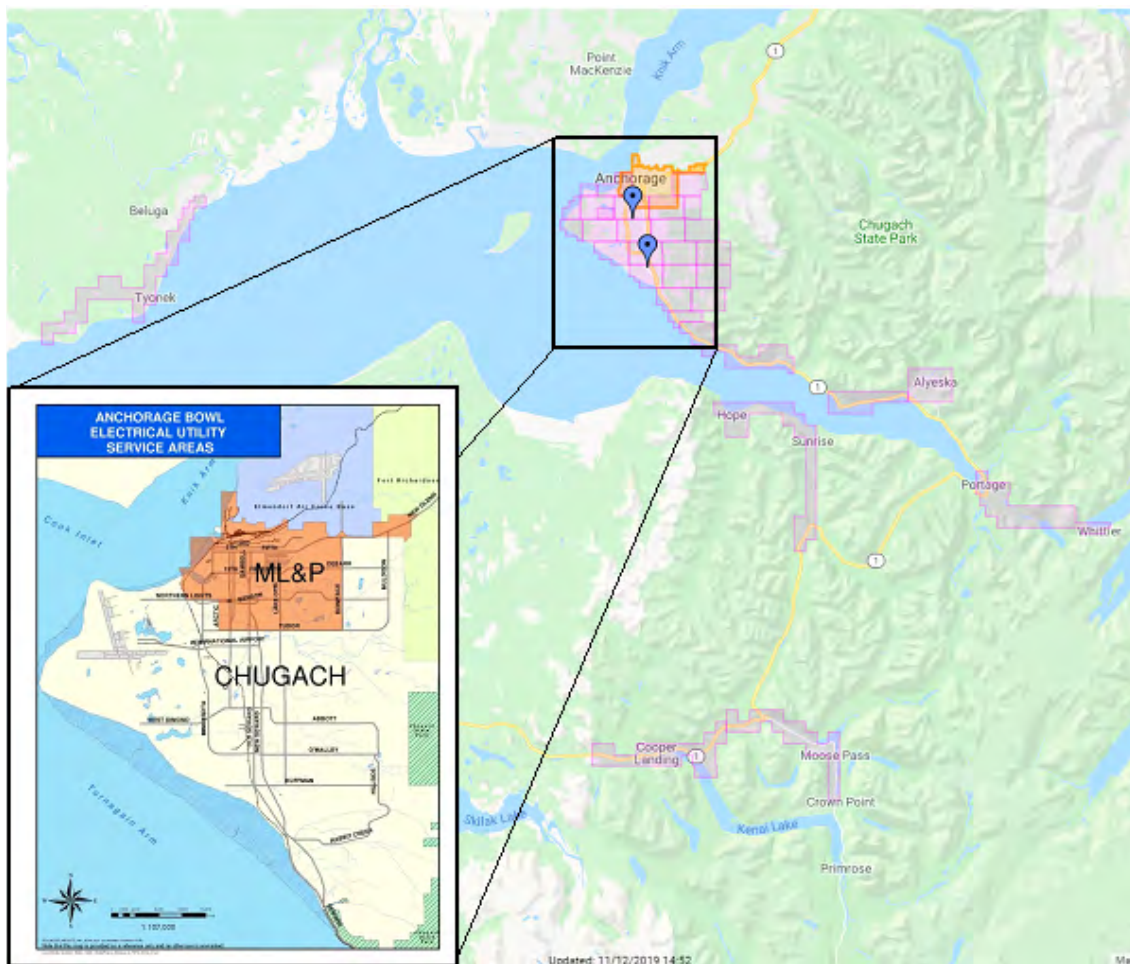


Figure 9.2. Chugach Electric (pink boxes) and ML&P (orange) service areas (source: Chugach Electric, 2019).¹

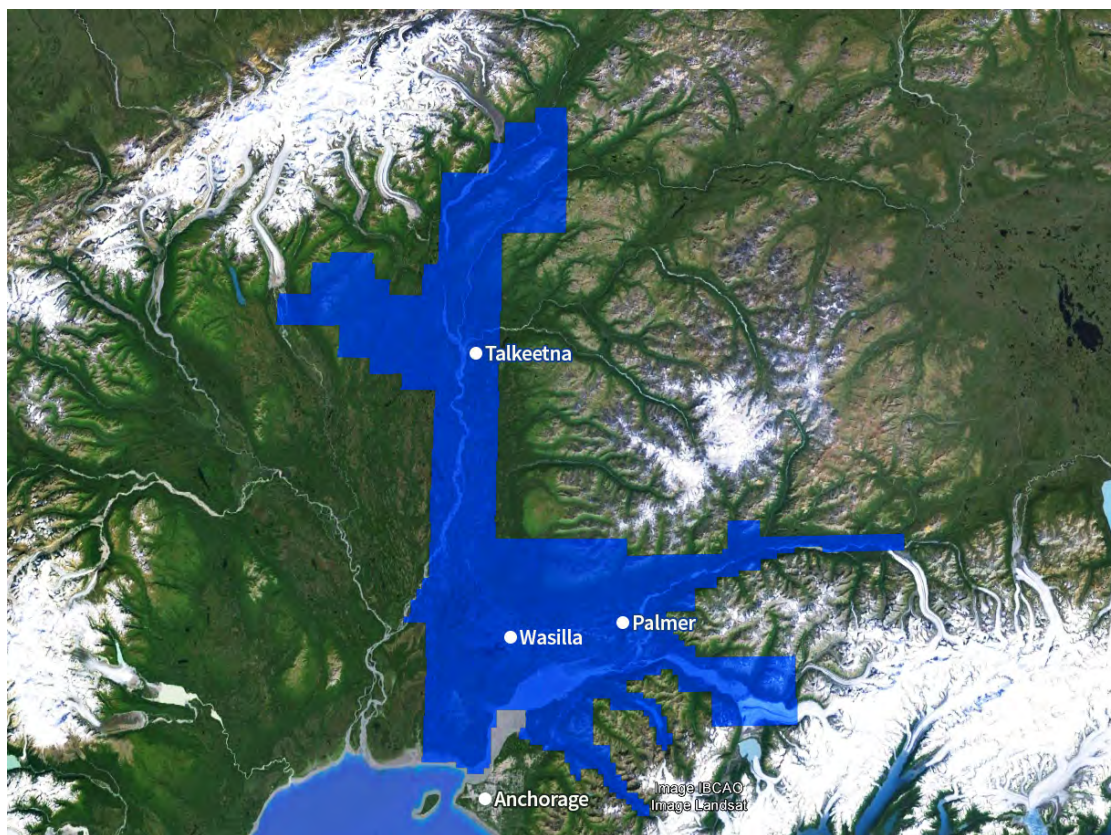


Figure 9.3. MEA service area (blue) (source: MEA, 2019).²

Of the three utilities, MEA had the most damage, which resulted in a loss of service to approximately 74% of MEA's more than 65,571 metered members (customers). This damage included 16 of 21 substations going off-line. Of these, four had major damage: Pippel and Briggs in Eagle River, Anderson in Big Lake, and Douglas in Willow (Zeller, 2019).³ Damage to the Eagle River substations included broken connectors and insulators (Holly, 2019).⁴ The 171MW Eklutna Generating Station was designed for strong earthquakes and remained fully operational (Holly, 2019), meaning that power was available once substation and other damage was repaired. MEA was able to restore power for all known outages by 3:30 a.m. on December 1 (Zeller, 2019).

The earthquake knocked the Intertie, a 170-mile (272-km) transmission line between Southcentral and Interior Alaska, off-line because of damage in the Mat-Su Valley, causing interior electric utility Golden Valley Electric Association to put backup systems into service to keep power on, which they were able to do successfully (Ellis, 2019).⁵

Chugach Electric reported outages to about 21,000 of its over 68,000 members. All but 10 customers had power restored as of 9 a.m. on December 1 (Chugach Electric, 2018).⁶ About 10,000 ML&P customers experienced outages, but all customers had power restored by 2:45 a.m. on December 1 (ML&P, 2018).⁷ Many outages in Anchorage were reported to be due to power lines swaying and making contact with each other (Shallenberger, 2018)⁸ or oil in transformers sloshing and causing the units to trip (DeMarban, 2018),⁹ rather than more serious types of damage. Figure 9.1 shows the number of members (meters or customers) out of service versus time, while Figure 9.2 shows service restoration, as a percentage of total members with power. These figures are based on outage and service restoration updates shared with the public by the utilities on Twitter (Figures 9.4 and 9.5).

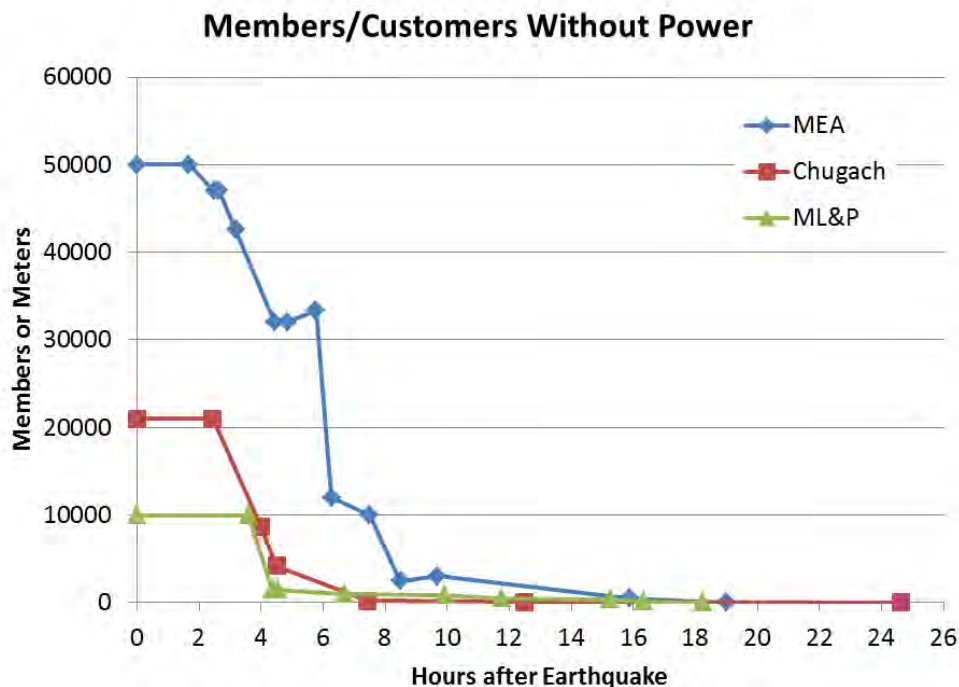


Figure 9.4. Earthquake-related outages versus time for the three electric utilities in the affected area.

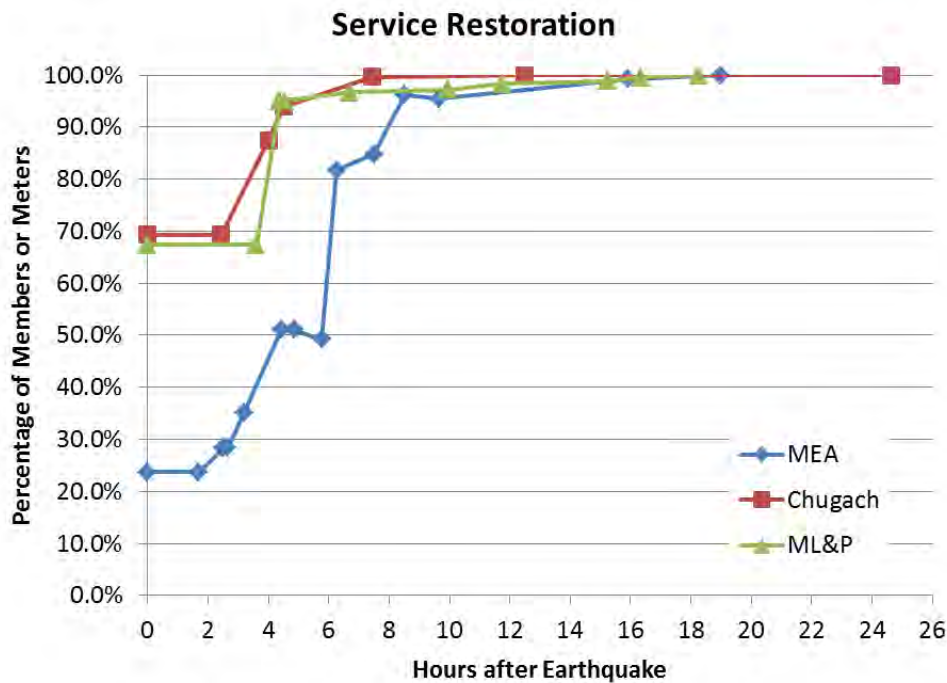


Figure 9.5. Service restoration for the three utilities in the affected area.

9.3 Water and Sewage Networks

Anchorage Water and Wastewater Utility (AWWU) has facilities from Girdwood to Eklutna, including two water-treatment facilities, as well as other infrastructure. In the aftermath of the earthquake, AWWU was not obtaining reliable readings from sensors, and they issued a notice to boil water until inspections were completed. Some restaurants reported that they were unable to operate during the notice to boil water. Although AWWU reported that there were no known water contamination issues, the boil-water notice was issued as a precautionary measure, given that water-main breaks can be a source of contamination. At 2:00 p.m. on December 2, AWWU issued a press release to lift the precautionary boil-water notice. AWWU reported that water-quality sampling and bacteriological testing were completed throughout the water distribution system, and on the basis of the results of the testing, it was determined that the water system was not contaminated because of the earthquake.

The day after the earthquake, AAWU received over 300 calls for water leaks within structures that could not be shut off by the owner, thereby requiring AWWU to turn off the water at the main. In addition to the water leaks, there were 15 water-main breaks, occurring primarily in northern communities in Eagle River, Chugiak, and Eklutna. Eighty piping main breaks were collectively identified, considering water and sewer. Breaks in the underground mains were caused by ground settling. Notable water-main breaks included the main that provides service to the municipality of Anchorage (MOA) Transit Administrative Office. On Airport Drive, a 12-inch water-main pipe pulled out of the joint because of ground movement, and an emergency excavation was made to enable repair, as shown in Figure 9.6. A shear break followed by asbestos-cement pipe erosion on Cordova led to flooding and an emergency excavation to make the repair, as shown in Figure 9.7. On First Avenue, a system surge caused failure of a corroded cast-iron pipe, which was removed and replaced with a polyvinyl-chloride pipe, as shown in Figure 9.8. Aging infrastructure is expected to have played a role in the observed damage to water mains. To repair damage, AAWU used four outside contractors, with crews working 24 hours a day for multiple weeks. Additional breaks in mains and facilities continued to be identified in the months following the earthquake.



Figure 9.6. Emergency excavation to repair a damaged water main on Airport Drive (photos: AWWU).



Figure 9.7. Emergency excavation to repair a damaged water main on Second Street, Cordova (photos: AWWU).

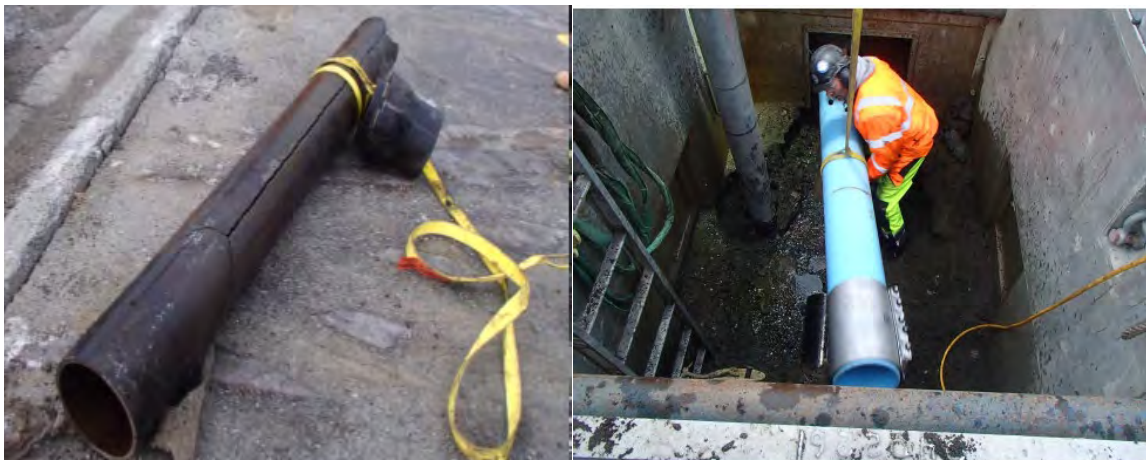


Figure 9.8. Emergency excavation to repair damaged pipe on First Avenue (photos: AWWU).

Following the earthquake, demand on the water system in Anchorage and Eagle River increased, likely because of the damaged water mains. The increased demand resulted in a noticeable drop in the water level at Meadow Creek Reservoir and Gruening Reservoir. Wells were turned on to meet the demand. Hypochlorite was trucked from Eklutna to critical well locations. Although the Ship Creek Water Plant was not fully commissioned at the time of the earthquake, hypochlorite generation was working, and Ship Creek was used as a source of additional hypochlorite.

In addition to damage to the water distribution system, damage to sewer systems was observed. Damage to the sewer service at a house is shown in Figure 9.9. The damage was caused by settlement of the house because of the earthquake. The homeowner hired a contractor to repair their portion of the damaged sewer service, and AWWU coordinated with the homeowner and the contractor to repair their portion of the damaged sewer service.



Figure 9.9. Emergency excavation to damaged sewer service (photos: AWWU).

In addition to the damage to water distribution systems and wastewater systems, structural and nonstructural damage to building infrastructure was observed at water and wastewater treatment facilities. The Eklutna Water Treatment Plant was fully operational after the earthquake, although there was structural damage that included concrete cracking and spalling, as well as movement between concrete elements (e.g., girders), as shown in Figure 9.10. At the Hyland Crest Booster Station in Eagle River, there was damage to concrete masonry units (CMUs) at the corners of perpendicularly oriented walls, as well as shifting of the roof, as shown in Figure 9.11. Structural damage at the Girdwood Wastewater Treatment Facility included failure of an overhead crane beam, as shown in Figure 9.12, and damage to tensioning rods. Nonstructural damage at the Girdwood Wastewater Treatment Facility included damage to suspended ceilings and cracks in the drywall at corners and at seams. Failure of the cable seismic systems occurred in the wastewater treatment plant in Eagle River.



Figure 9.10. Structural damage at Eklutna Water Treatment Plant (photos: AWWU).



Figure 9.11. CMU damage at the Hyland Crest Booster Station in Eagle River (photo: AWWU).



Figure 9.12. Failure in overhead crane beam at Girdwood Wastewater Treatment Facility (photo: AWWU).

AWWU reported a number of lessons learned as a result of the earthquake. The lessons learned were grouped into the areas of communications, training, resources, and documentation. With regard to communications, specific issues identified included radios, which are typically mounted in trucks, whereas most work is done outdoors. Satellite phones did not work inside of buildings. There was a limit of 20 people on phone bridges. Additionally, not all supervisors had phone numbers for staff. With regard to training, new staff lacked training on how to respond to the incident. The hazard-response plan needed to be updated, and new staff needed to be trained. While desktop drills had been practiced, hands-on training drills had not been performed prior to the earthquake. With regard to resources, it was identified that it is important to have the proper equipment staged throughout the area and that it is necessary to have sufficient food resources to endure a larger earthquake. Having adequate fuel storage is also essential. With regard to documentation, it was identified that everything needed to be in place beforehand.

It is worth mentioning that there are 70 dams in Southcentral Alaska, and they were not affected by the earthquake. (Federal Emergency Management Agency (FEMA), personal comm., 2019).

9.4 Oil Pipeline and Gas Supply

The Alaska Pipeline was temporarily shut down for inspections. Within a few hours, all inspections were completed. No damage to the pipeline was identified by the inspections, and the pipeline was reopened 12 hours following the earthquake.

There were hundreds of gas leaks at houses throughout the affected area because of rigid-pipe connection failures, which often occurred at pipes connected to water boilers that were insufficiently restrained. ENSTAR typically has approximately 2,000 leak calls in a year. However, from November 30 through December 10, ENSTAR received 3,028 leak calls. Twenty percent of the leaks were fixed by morning on Monday, December 3. ENSTAR had 13 leak surveyors/line locaters, and nine distribution technicians surveyed 570 miles of underground steel main. Eagle River was surveyed twice. Six underground leaks were identified on the distribution system, and two steel lines were pulled out of service following the earthquake. ENSTAR hired contractors to help out with repairs. In addition to gas leaks and damaged gas lines, The ENSTAR call center on Spenard Road was closed because concern about airborne asbestos. ENSTAR reported some observations and lessons learned from the events regarding gas lines:

- It is suggested that energy companies store fuel for their vehicles at their service areas. Eagle River lost power following the earthquake, and, therefore, no fuel pumps were available.
- Leaks often occurred at hard-pipe unions, and many simply needed tightening. More routine maintenance is recommended.
- Appliances with flexible gas piping connectors did fine. Use of flexible gas piping connectors over rigid connectors is recommended.
- Water heaters for trailers received significant damage.
- Appliance vents were disconnected.
- It is recommended to inform the public of a suggested post-earthquake protocol for gas lines and meters. There was an example of a group of people that turned off a whole street of gas meters. ENSTAR was then called off of potential leak calls to turn the meters back on. Gas was not smelled in this case, and it was not necessary to turn off the service. When the public is better informed on protocol, the post-earthquake response is more efficient.

9.5 Telecommunications

Outages of telecommunication networks, including some cell phone services, were observed after the earthquake; however, the telecommunication sector appears to be the least affected among lifelines and utilities. Both GCI and AT&T cell phone service providers performed checks on their networks and swiftly fixed outages and urged people to use text messages or social media rather than phone calls, except for emergency situations, to reduce pressure on the networks. GCI stores were affected by structural and nonstructural damage, and many were closed for a few days. Two of Anchorage's GCI offices (Midtown Mall and Victor and Diamond) remained closed through December 4. One GCI store in Anchorage (Victor and Diamond) remained closed on December 5. Most other GCI stores were open by December 5. Both providers waived service charges in the affected regions. Emergency sections stayed open, but all other MOA sections stayed closed through the following week. One of GCI's office buildings had moderate earthquake damage to foundations and floors, as well as to water piping, and was closed for a few months following the event. GGI relocated 100 other employees because of damage in the KTVA building (a GCI company, Figure 9.13).



(a)



(b)

Figure 9.13. (a) KNBA studios damage (photo: ADN) and (b) KTVA office damage (photo: CNN).

A tsunami warning was issued to all residents of the Anchorage Bowl, and cell phone providers texted the warning to customers, including those located in areas not at tsunami risk, causing some panic and evacuation of residents. The tsunami warning was cancelled 2 hours later.

The postal service was affected by damage in their offices and operated at reduced capacity until Monday, December 3, when operation was restored to normal. The KTVA television station building was extensively damaged, and the station needed to relocate and split employees among multiple locations until April, with reduced capacity.

9.6 Railway System

Inspection of tracks and bridges on the Alaska Railroad was completed on December 2. On December 2, all landslides on the Alaska Railroad were cleared south of Anchorage to allow the resumption of freight from Whittier to Anchorage (Alaska Department of Transportation and Public Facilities (ADOT&PF), 2018),¹⁰ so the Alaska Railroad reopened the Seward-Whittier-Anchorage route 36 hours following the event.

Three areas north of Anchorage were identified as impassible (for more than 1 mile), preventing trains from traveling between Anchorage and Fairbanks. Examples of damage are provided in Figure 9.14. Lateral spreading and liquefaction were observed at several segments. One of the sites was near Nancy Lake, about 45 miles north of Anchorage, where

ground cracks up to 4 feet wide, 3 feet deep, and 150 feet long were observed on either side of the tracks (Associated Press, 2018).¹¹ As of December 3, service between Anchorage and Fairbanks was resumed on the Alaska Railroad (ADOT&PF, 2018). Regularly scheduled freight and passenger service on the Alaska Railroad was resumed on December 4. Passage through portions of the track south of Eklutna Lake and south of the Cheri Lake Road were restored following earthquake damage (Boots, 2018¹²; *Anchorage Daily News*, 2018).¹³ In addition to the damage to the railway, there was water damage to the Alaska Railroad operation center in Anchorage (Associated Press, 2018). In addition to the delays in freight train service, there were delays to passenger train service. The first passenger train ran on December 6. Holiday trains resumed service on the second weekend after the earthquake (i.e., 8 days after the earthquake).



Figure 9.14. Damage to Alaska Railroad (photo: Associated Press, 2018).

9.7 Airports and Flight Operation

The Ted Stevens Anchorage International Airport remained open after the earthquake but was operating at a reduced capacity. Initial damage reports indicated broken glass from windows and light fixtures and damage to water mains at the terminal. Power was not lost, although heat was lost. Escalators and elevators were initially out of service, but most were returned to service by the early afternoon. The air-traffic-control tower was evacuated. Transportation Security Administration baggage screening was down, and outbound flights were delayed because of inspections. Inbound flights were on hold by order of the Federal Aviation Administration for a few hours and then were allowed to land starting at 1:15 p.m., although both arrivals and departures were experiencing delays. The airfield was operational 1 hour following the main shock. The upper arrivals ramp and lower departures ramp were closed because of damage, with detours in place for drop-offs and pickups at the taxi and shuttle bus queues. Drivers were encouraged to use the cell phone lot and parking garage because of the limited space in the pickup and drop-off area. Alaska Airlines suspended service to Anchorage for a period of roughly 1.5 hours. Similar action was taken by Delta Airlines, with service resumed around 2:00 p.m. local time. Delta indicated operation of a full schedule, with delays. Anchorage Airport restored full operational functionality at 3:18 p.m., nearly 7 hours following the earthquake. Kodiak Airport was initially closed but was reopened roughly 2 hours after the earthquake. Merrill Field Airport suffered minor damage.

9.8 Performance of Port of Alaska

An aerial view of the Port of Alaska is provided in Figure 9.15. Damage at the Port of Alaska resulting from the earthquake included substantial dock and shore infrastructure failures, as well as damage to seismic/expansion joints. Failures at the seams of pile welds were particularly prevalent, and in many instances, these failures were only possible to detect in the spring of 2019, after snow melted. The port has 1,400 piles, many of which were in service beyond their intended design life and were in a deteriorated condition prior to the earthquake because of the harsh environmental conditions. In addition to visual inspections of piles that were conducted at low tide, ultrasound imaging was used to assess structural damage because of accessibility issues at many locations. It was determined that weld failures had occurred in piles at spiral seams, butt welds, and vertical seams. Weld failures on spiral seams, shown in Figure 9.16, were particularly prevalent under Petroleum, Oil, and Lubricants Terminal (POL) 2, where it was reported that approximately 20% of the deck piles were compromised. Failures of butt welds were particularly prevalent under POL 1 and Terminal 1. Weld failures on

vertical seams, shown in Figure 9.17, were limited, with most occurring under Terminal 2. Damage at the welded seams of pile jackets was attributed to the welding steel used in the 1960s and 1970s, which differed from modern-day welding steel. Specifically, the older steel was more galvanically reactive than the main pile steel, such that the cathodic behavior of the welding steel caused more rapid corrosion relative to the main pile steel. Following the earthquake damage to pile jackets, repairs were made. Fender pile failures and storm drain failures, shown in Figure 9.18, were also observed.



Figure 9.15. Aerial view of the Port of Alaska. (photo: Port of Alaska)



Figure 9.16. Weld failure in spiral seam of wharf pile (photo: Port of Alaska).



Figure 9.17. Weld failure in vertical seam of wharf pile at Terminal 2 (photos: Port of Alaska).



Figure 9.18. Fender pile failures and dock repairs (photo: Port of Alaska).

In addition to the observed structural damage, nonstructural damage was observed. As shown in Figure 9.19, nonstructural damage included damage to dock lights and cameras, as well as failure of wires and connections in cathodic protection systems. Nonstructural damage to office buildings was consistent with observed nonstructural damage to buildings elsewhere.



Figure 9.19. Nonstructural damage to dock lights, cameras, and connections and wires of cathodic protection systems (photos: Port of Alaska).

In addition to the structural and nonstructural damage, geotechnical damage was observed at the Port of Alaska as a result of the earthquake. Failure of the shoreline was observed adjacent to Terminal 1, as shown in Figure 9.20. Slope failures and liquefaction, shown in Figure 9.21, caused movement of the shore. Additionally, slope failures were observed along the full length of container docks, as shown in Figure 9.22. Although slope failures occurred near the dry barge berth, a tugboat and barge that were dry-docked remained on their blocks, as shown in Figure 9.23. Repairs that are underway are shown in Figure 9.24.



Figure 9.20. Shore failure near Terminal 1 (photo: Port of Alaska).



Figure 9.21. Yard slope failure and liquefaction moved shore (photo: Port of Alaska).



Figure 9.22. Slope failures along the length of container docks (photos: Port of Alaska).



Figure 9.23. A barge and tugboat remain on their blocks despite being in close proximity to slope failures (photos: Port of Alaska).



(a)



(b)

Figure 9.24. Port of Alaska earthquake repairs underway (photos: (a) Port of Alaska, (b) Wael Hassan).

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10.1 Overview

On November 30, 2018, an Mw7.1 earthquake struck the west side of the Cook Inlet. While the state of Alaska fared this event extremely well, this earthquake was not representative of “the Big One.” Experienced shaking duration and intensity from the Cook Inlet earthquake was below the design level for modern buildings. Damages sustained, and weaknesses identified by this earthquake, demonstrate opportunities for improvement at all levels of government; we will learn from this event and continue to support and build a more resilient Alaska.

The following recommendations evolved from post-event findings, discussions, and meetings among state, federal, and local stakeholders. Together, they provide a framework designed to achieve agency coordination and cooperation. The success of these actions will require a cooperative effort among federal, state, tribal, and local agencies. These stakeholders included the following:

- the Alaska Department of Community and Regional Affairs,
- the Alaska Department of Homeland Security and Emergency Management,
- the Alaska Planning and Design Commission,
- the Alaska Seismic Hazards Safety Commission,
- the American Society of Civil Engineers,
- the Earthquake Engineering Research Institute,
- the Matanuska-Susitna Borough,
- the Municipality of Anchorage,
- the Municipality of Anchorage Geotechnical Advisory Commission,
- National Earthquake Hazards Reduction Program partners: the Federal Emergency Management Agency (FEMA), U.S. Geological Survey, and National Institute of Standards and Technology,
- the Structural Engineers Association of Alaska, and
- the University of Alaska.

Agencies other than those identified above may be involved in implementing this report's recommendations.

Findings and recommendations have been sorted into two categories, those meant to improve state and local hazard-mitigation planning processes and those meant to strengthen infrastructure resilience to earthquakes.

10.2 Recommendations to Improve State and Local Hazard-Mitigation Planning Processes

10.2.1 Overview

FEMA supports hazard-mitigation planning as a means to:

- foster partnerships for natural-hazard mitigation,
- promote more resilient and sustainable states and communities, and
- reduce the costs associated with disaster response and recovery.

FEMA encourages states to focus on a comprehensive and inclusive planning process to support mitigation throughout state government and at the community level. Continuous coordination among state agencies and communities is the key to achieving mitigation goals and long-term resilience.

**This chapter has been contributed by FEMA Region 10 to summarize its risk mitigation recommendations based on an independent Nov 30, 2018 earthquake investigation that was not associated with the EERI Field Reconnaissance Mission presented in this report. The EERI Field Reconnaissance Mission's main report conclusions and recommendations are presented in Chapter 11.*

10.2.2 Findings

- After the event, state and local officials were aware of geographic areas that likely received higher damages due to soil performance, lack of maintenance, or substandard building codes and/or enforcement; however, residents, businesses, and agencies were unaware of their vulnerabilities.
- A comprehensive natural-hazard risk assessment is needed for all essential facilities, including schools and hospitals. Risk assessments previously completed are weak and not representative of true vulnerabilities. The needs and vulnerabilities that were identified through these assessments are not referenced or integrated into local or state hazard-mitigation planning or other risk-reduction processes, leaving a path toward resilience unclear.

10.2.3 Recommendations to Improve State and Local Hazard-Mitigation Planning Processes

1. After the event, state and local officials were aware of geographic areas that likely received higher damages due to soil performance, lack of maintenance, or substandard building codes; however, residents, businesses, and agencies were unaware of their vulnerabilities.

The State Hazard Mitigation Advisory Committee (SHMAC) and Local Emergency Planning Committees (LEPCs) should

- a) **Include representation from local geotechnical engineers, builders/developers, building owner organizations, school districts and education representatives, housing and finance, and infrastructure partners.** A planning team inclusive of the above stakeholders will generate feasible and politically supported mitigation strategies and foster an increased awareness of local vulnerabilities to hazards, thus instilling a culture of preparedness among Alaskans.
 - b) **Meet routinely to collaboratively develop, maintain, track, update, and implement mitigation actions.** Regular meetings and engagement of the SHMAC and LEPCs will ensure relevancy of proposed risk-reduction actions, increase awareness of available funding sources and timelines, and provide an increase in opportunities for mitigation investment. Additionally, these regular meetings should increase coordination between hazard-mitigation goals and existing future development and land use plans, reducing costs and impacts of future disasters.
 - c) **Publicize risk-reduction planning meetings and meeting notes.** Informing the general public and creating awareness of the state and local government interests in supporting risk-reduction efforts will build a culture of preparedness among Alaskans; increased awareness will allow for more informed decision making and the integration of mitigation planning into all aspects of community planning and development.
2. A comprehensive natural-hazard risk assessment is needed for all essential facilities, including schools and hospitals. Risk assessments previously completed are weak and not representative of true vulnerabilities. The needs and vulnerabilities that were identified through these assessments are not referenced or integrated into local or state hazard-mitigation planning or other risk-reduction processes, leaving a path toward resilience unclear. Risk assessment and vulnerability information should be improved by
 - a) **Ensuring school rapid visual screening (RVS) studies (1) cover a large pool of buildings representative of seismic vulnerabilities (determined by age, code benchmark dates, and structural type), (2) be followed up with a detailed structural evaluation for those identified as vulnerable, and (3) support actionable mitigation strategies at both state and local levels.** Sharing of RVS and school risk-assessment data will increase awareness of vulnerabilities to all natural hazards and increase opportunities for investments in risk reduction. Additionally, these results should inform disaster-response planning (prioritization of post-event inspection and response needs and evaluation of designated shelter sites), thus helping Alaska to be more prepared for future disasters.
 - b) **Seeking alignment of school-district and other essential-facility Capital Improvement Plan budgets with state and local risk-reduction budgets.** State and local mitigation funds can be stretched further, providing increased investments in mitigation when aligned with existing school-maintenance and facility-planning processes.
 - c) **Ensuring vulnerability and risk-assessment data from essential facilities are integrated into the local and state hazard-mitigation planning process.** Identified vulnerable buildings can be prioritized at state and local levels for seismic retrofits, compliant with modern seismic standards. Response plans can

also be updated with this information, updating areas anticipated to receive higher damages due to lack of seismic stability. An inventory of vulnerable structures and systems may incentivize investments in risk-reduction efforts and help communities better prepare for disasters.

10.3 Strengthening Infrastructure Resilience to Earthquakes

10.3.1 Overview

A recent engineering analysis of national building codes revealed that only 7,265 of 23,000 communities have building codes with disaster-resistant provisions incorporated for both commercial and residential codes. Consumers are largely unaware of the dangerous gap between building code adoption/enforcement and disaster risk. They do not understand that they may live in a community without the protection of current, modern building codes and standards.

The Alaska Constitution and applicable statutes delegate Alaska building code requirements by borough and city class; there is no adoption of a statewide standard. Most cities that are not required to have building codes do not. Those that do have building codes face enforcement difficulties due to lack of funding, lack of staff, and the geographic size of the enforceable area.

10.3.2 Findings

- Post-event inspections throughout declared boroughs found a patchwork of regulatory oversight and enforcement for compliance with state and local codes and seismic standards.
- State and local level governments do not have enough qualified staff to successfully support regulatory oversight and enforcement or public awareness and education for compliance with seismic standards.
- Because of the lack of code adoption and enforcement, the true vulnerability of Alaska's building stock is unknown.
- In most cases, nonstructural damage was the reason for building closures due to the earthquake.
- State and local level governments do not have enough trained staff to apply for and manage federal grant funding and meet matching requirements.

10.3.3 Recommendations to Strengthen Resilience to Earthquakes

1. Post-event inspections throughout declared boroughs found a patchwork of regulatory oversight and enforcement for compliance with state policy, regulations, local codes, and seismic standards. Transparency and consistency of minimum seismic standards should be accomplished by
 - a) **Consolidating code adoption and enforcement practices under one state entity.** Consolidating of codes currently falling under regulatory authority of the State Fire Marshal, Department of Labor, and other various agencies will result in a transparency of minimum building standards and a consistent approach to code enforcement from the state and local governments. Building code adoption and enforcement is one of the strongest strategies jurisdictions can use to increase their resilience against the effects of natural hazards.
 - b) **Establishing a statewide standard for building practices.** The state should adopt and enforce the most current building and residential codes, and it should encourage adoption and enforcement by all local jurisdictions (currently, the 2018 International Building Code (IBC) and the 2018 International Residential Code (IRC)). At the time of the November 30 earthquake, the 2012 IBC was adopted at the state level, and there was no statewide standard for residential homes. Since adoption of the 2012 codes, improvements have been made to the understanding of the seismic performance of buildings, and these new findings are represented in the 2018 IBC and IRC. Residential building codes make homes safer and stronger and are supportive of closing the insurance gap via a reduction in filed claims. An updated and consistent building code will promote best practices in residential and commercial construction, reduce future disaster losses, and support more prepared and resilient communities.
 - c) **Encouraging the adoption and enforcement of stronger seismic safety provisions, when appropriate.** Areas of known soil performance concerns, steep slopes, etc., should require a geotechnical assessment prior to permitting. Seismic standards should be established and placed on saturated soils and excavation and fill practices for new construction. These practices will minimize the impacts of seismic hazards on development and enhance safe construction in high-hazard areas. Prioritizing seismic safety with construction will reduce the losses associated with future earthquakes.

- d) **Educating state and building design professionals and contractors on state seismic risk and construction best practices.** Building design professionals should possess a basic understanding and appreciation of seismic hazards (e.g., earthquake sources and activity, earthquake-induced ground motions and ground failure, tsunamis, etc.), as well as seismic engineering (i.e., evaluation and design to mitigate seismic risk to the populace and infrastructure). Engineering and building design professionals should be required to have completed a university-level or equivalent course addressing seismic hazards in order to practice in the state of Alaska. Contractors should be required to pass FEMA's P-593 Course, "Seismic Rehabilitation Training for One and Two-Family Dwellings." Requiring knowledge of seismic hazards and mitigation practices of the engineering and design-build community will contribute to a culture of seismic preparedness and foster innovation in the field of seismic design.
 - e) **Requiring independent third-party inspections of structural design and construction.** To ensure proper enforcement of compliance to minimum seismic standards, review of design and inspection of construction is needed prior to issuance of building permits and certificates of occupancy for all construction. Inspection duties should be delegated to local jurisdictional authorities and the state to avoid conflicts of interest between builder and inspector. Third-party inspections of design and construction practices will result in development of a more resilient building stock and reduce the costs of future disasters.
2. State and local level governments do not have enough qualified staff to successfully support regulatory oversight and enforcement or public awareness and education for compliance with seismic standards. To successfully implement and enforce adopted regulations, the state of Alaska and local governments should consider
- a) **Evaluating workloads and primary responsibilities of existing staff.** A resilient building stock begins at the permit counter. Priority should be given to ensuring design and construction work meet minimum state and local seismic standards. If current staffing levels do not support the ability to meet demand, a plan should be developed to increase adequate staffing levels. Ensuring adequate staff levels, manageable workloads, and promoting meaningful work contributing to risk-reduction goals will increase job satisfaction levels and support increased staff retention.
 - b) **Develop a training program/process for code-enforcement staff at the state and local level on seismic codes and enforcement.** Seismic codes and standards have no value if they are not implemented and enforced. To ensure implementation, staff tasked with enforcement should be well-trained on the value and importance of these regulations. Staff should also be educated on the enforcement process and the resources and tools to support their enforcement. Educated and empowered enforcement staff will feel supported in their role, have an increased sense of job satisfaction, and will be supportive of staff-retention goals.
3. Because of the lack of code adoption and enforcement, the true seismic vulnerability of Alaska's building stock is unknown. Awareness and understanding of seismic vulnerabilities can be improved by
- a) **Conducting a public awareness campaign on building codes for earthquake safety.** There is a need for meaningful engagement of public officials, developers, realtors, contractors, building owners, and the general public about seismic hazards and building requirements. Targeting individual audiences with messages and attainable actions to take ownership of risk reduction will motivate investments in mitigation and build a culture of preparedness.
 - b) **Developing a homeowner-friendly program that provides guidance on home retrofits and earthquake safety.** A retrofit guidance program depicting a clear path to increased seismic safety through detailed do-it-yourself steps or engineer-selection guidance for repairing damaged foundations, anchoring homes, and strengthening shear and cripple walls will build a culture of seismic preparedness and create a more educated residential homeowner. As a result of this program, homeowners will know what seismic design qualities to look for in new homes and will encourage home builders to highlight their adherence to seismic standards.

4. In most cases, nonstructural damage was the reason for building closures due to the earthquake. Electromechanical issues, sprinkler-head failures, weak connections, pipe breaks, and sliding water boilers were the primary reasons buildings were closed after the November earthquake. To reduce these types of nonstructural damages from earthquakes, the state of Alaska should consider
 - a) **Investigating the performance of different types of fire-sprinkler piping, connections, and bracing.** Recommendations for approaches to reduce the potential for pipe breaks and the probability of unintended water release should be researched and developed. Consideration should be given to investigating new technologies or approaches to improved performance of fire sprinklers.
 - b) **Requiring inspections of mechanical, electrical, and plumbing (MEP) equipment during construction.** Installation of MEP equipment is often completed without inspection by a building official or design professional. Approaches for requiring equipment inspections during construction should be explored and implemented.
 - c) **Increasing and improving education on engineering nonstructural components for seismic design.** Architects, mechanical engineers, plumbing engineers, electrical engineers, fire-protection engineers, information-technology consultants, and others associated with nonstructural components should be trained to better understand the seismic performance implications of improperly designed or installed nonstructural components.

The above recommendations were developed collaboratively. They are not intended to be implemented by one sole agency; collaboration is critical, not just during a crisis, but before as well. To achieve resilience, all levels of government, nonprofit organizations, private-sector businesses, and individual communities need to work together to prepare for and mitigate disasters before they happen. The ability of Alaska to be truly ready for the next big earthquake depends on everyone knowing and understanding the part they play in the state's collective resilience.

11 REPORT'S CONCLUSIONS, LESSONS, AND RISK MITIGATION RECOMMENDATIONS

11.1 Summary

On November 30, 2018, at 8:29 a.m. Alaska Standard Time, Southcentral Alaska, the most populous region in Alaska, was violently shaken by an Mw 7.1 earthquake. This was the largest earthquake in the United States close to centers of population in over 50 years. The earthquake was 46 km (29 miles) deep and epicentered at 61.346°N 149.955°W, 12 km north of Anchorage and 19 km west of Eagle River. The event affected some 400,000 residents in the Municipality of Anchorage and the Matanuska-Susitna (Mat-Su) Borough. The earthquake caused widespread damage in roads and highways, nonstructural components, nonengineered buildings, older buildings, and buildings and infrastructure on poorly compacted (and uncompacted) fills. Minor structural damage in a new engineered building was observed. A significant percentage of the damage was due to geotechnical failures. Within the first 9 months, the mainshock generated a vigorous aftershock sequence with over 10,000 aftershocks, 7 of which were larger than M5 and 50 of which were larger than M4.

Building stock diversity in the region allows its use as a large testbed to observe how building practices impacted earthquake damage levels. Anchorage Bowl is heavily free-field instrumented, and more than eight structures in Anchorage are well instrumented with structural arrays. The prevailing peak ground acceleration (PGA) in the region was 0.2g-0.3g, although individual sites may have experienced stronger shaking because of local soil conditions. In general, the ground motion at most sites was about 50%-60% of the design-basis earthquake acceleration. No loss of life or full collapses were reported, although a few isolated serious injuries and partial collapses took place.

The earthquake caused widespread damage in roads and highways, nonstructural components, nonengineered buildings (that exist widely in the region), older buildings, and buildings and infrastructure on poorly compacted (and uncompacted) fills. Minor structural damage in new engineered building was observed. This chapter summarizes damage observations by the EERI Field Reconnaissance Team presented in this report (Chapters 1-9) and draws conclusions and lessons from this event as well as presenting some recommendations to reduce seismic risk and improve resiliency following major earthquakes.

11.2 Seismology Observations and Lessons

- The earthquake was located at a depth of approximately 46 km, and the epicenter is identified at 61.346°N 149.955°W, approximately 12 km north of Anchorage and 19 km west of Eagle River.
- The earthquake was a normal faulting intraslab event within the subduction Pacific Plate.
- Maximum PGA recorded at a strong motion station was 0.56g at the Rabbit Creek Fire Station (K215).
- Average values of PGA and PGV across Anchorage were 0.3g and 25 cm/s, respectively.
- The main event had a significant duration of approximately 15 to 20 seconds.
- From November 30, 2018, through August 2019, more than 10,000 aftershocks were recorded, 300 of which were felt.
- Fifty large aftershocks occurred within 45 days of the main event with magnitude greater than M4, 7 of which occurred with magnitude between M5.0 and M5.7.
- There were 80 aftershocks on the first day (November 30), 3 of which were larger than M5.0. The first strong aftershock was M5.8 at 8:35 a.m., only 6 minutes following the main event.
- The aftershocks formed two clusters, a shallow east-dipping southern cluster and a steep west-dipping northern one, forming an aftershock zone 20 km wide and 25 km long.
- The aftershock continued for 2.5 years following the main event as predicted. The latest large aftershocks were M5.3 on Feb 27, 2021 and M4.9 on April 28, 2021.
- The aftershock sequence exacerbated damage in many buildings.
- Anchorage Bowl is well instrumented, which helped correlate damage to recorded ground motions and understand local site effects.
- Anchorage Northern Communities, Girdwood and Mat-Su Borough, lack any seismic instrumentations. Shaking was only estimated using USGS's "Did You Feel It?" (DYFI) tool.
- The State of Alaska is advised to invest in instrumenting these areas for better understanding of the seismic hazard of their existing infrastructure and to help economic growth via new project establishments in these areas.

11.3 Lessons from Structural Damage in Buildings

11.3.1 Building Stock and Damage Distribution

- Nonengineered and low-quality construction buildings posing increased risk of severe earthquake damage and collapse exist in Anchorage. About 42% of Anchorage Bowl's building stock was built between 1975 and 1990 during the Trans-Alaska Pipeline System construction boom era. During that period, construction demand and speed far exceeded the capacity of the Municipality of Anchorage in code enforcement, leading to serious concerns about the construction quality of these buildings. These concerns were validated following the November 2018 earthquake, as most of Anchorage's earthquake damage was concentrated in these types of buildings, many of which are completely nonengineered.
- The older existing buildings' seismic risk problem is evident in Anchorage and the Mat-Su Borough. Buildings predating modern seismic codes constitute the majority of building stock in the region. Approximately 73% of Anchorage Bowl building stock was constructed before 1990, when the Municipality of Anchorage started to fully enforce building codes, including seismic details, in Anchorage. Older building seismic deficiencies posing increased collapse risk during the maximum considered earthquake (MCE) such as soft/weak story, nonductile concrete, nonductile concrete masonry unit (CMU), pre-Northridge welding, and building structural irregularities are common in this large pre-1990 building stock in Anchorage. In addition, 12% of Anchorage Bowl's current building stock was built before 1964 without proper seismic design or details. Studies to assess the seismic risk of Southcentral Alaska's existing buildings problem under MCE scenarios are needed, especially for critical and essential facilities and high-occupancy buildings.
- Nearly 80% of Anchorage Bowl's building stock was built before UBC 1997, when the Northridge Earthquake revealed the deficient welding techniques in steel construction. Compared to current codes, UBC 1997 is considered the earliest code to ensure "Life Safe" performance during strong shaking for most types of structures. IBC 2000 is considered the earliest code appropriate for school seismic safety. Nearly 50% of the tallest high-rise buildings in Anchorage with a large number of daily users and hundreds of steel-frame mid-rise and low-rise buildings may have deficient pre-Northridge welds, posing increased seismic collapse risk.
- The nonengineered building problem is evident in Anchorage's Northern Communities, Girdwood and most of Mat-Su Borough. About 14,000 buildings in Northern Communities are outside the Anchorage Municipality Building Safety Service Area (ABSSA). Building permits, code-conforming engineered design, plan review, and construction inspection are not required or enforced in these areas, including in commercial and public buildings. This led to nonengineered construction of the majority of these buildings, proven by post-earthquake damage inspections performed by the Earthquake Engineering Research Institute (EERI) Team, ATC-20 Team, Federal Emergency Management Agency (FEMA) Team, Anchorage Municipality, and several local structural engineers. This situation may pose significant seismic damage and collapse risk under the MCE scenario of a substantial number of buildings with significant seismic deficiencies in Northern Communities.
- The maximum recorded PGA for the event was 0.56g in Rabbit Creek (South Anchorage). The prevailing PGA in Anchorage was 0.2g-0.32g, with the exception of isolated spots receiving more than 0.32g. Because of the lack of seismic instrumentation in the Eagle River area, there is little scientific evidence other than DYFI reports to suggest that its shaking intensity was higher than Anchorage. Several of Anchorage's sites received higher than 0.4g and did not experience the heavy level of damage witnessed in Eagle River. Mat-Su Valley has only three accelerometers, thus it was not possible to build accurate PGA maps for the region. However, based on the damage investigation, its damage was heavier than Anchorage and less significant than Northern Communities. The north-south component of the ground motion appeared to be more significantly affected buildings in Anchorage than east-west component.
- The prevailing short period and 1-second period spectral accelerations in Anchorage Bowl were 0.6g-0.9g and 0.1g-0.3g, respectively. The highest 1-second period spectral acceleration was 0.4g in Anchorage downtown. The highest short-period spectral acceleration was 1.25g in Rabbit Creek (South Anchorage) and Sand Lake (West Anchorage).

- Shaking intensity at most sites with period range of 0.4-1 second in Anchorage Bowl, observed from spectra generated from seismic instrumentation stations, did not exceed 50%-60% of the design-based earthquake spectrum. Thus, the November 2018 earthquake was not a sufficient test to assess the actual seismic vulnerability of Southcentral Alaska's built environment. The level of structural damage observed does not imply high quality of construction or the strictness of building codes since most buildings were not truly tested. Realistic seismic risk studies for Southcentral Alaska under MCE scenarios are much needed.
- Eagle River and Chugiak areas experienced the heaviest structural damage in Southcentral Alaska during the earthquake, especially single-family wood buildings and CMU buildings. The ratio of red-tagged buildings to building stock size in Northern Communities outside the ABSSA zone was 18-20 times higher compared with that within ABSSA. Many buildings in Northern Communities lacked a defined lateral load-resisting system. Anchorage Bowl and Mat-Su Borough experienced light structural damage except in some CMU buildings. Sand Lake and Jewel Lake neighborhoods in Anchorage exhibited relatively heavier damage than the rest of Anchorage; however, it was mostly soil failure related without serious structural damage. The highest PGA was recorded in Rabbit Creek (South Anchorage), yet minimal damage occurred there. Pre-1990 Anchorage buildings, especially those built 1975-1990, had more structural and nonstructural damage than those built after 1990. Short period low-rise and mid-rise buildings had more damage than relatively high-rise buildings in Anchorage.
- Based on these observations, the same old lesson of the importance of following building codes can be confidently reaffirmed. Following building codes should not be optional under any circumstances in any habitable building, or in nonbuilding structures serving the public. Building codes should be enforced, especially in areas with high seismic hazard.
- Based on structural damage and distribution observed, it is clear that nonengineered buildings in Southcentral Alaska constitute a significant seismic risk to the life or property of a large population in the region. Statistics on the number of people who live in nonengineered or poorly constructed buildings are not readily available, but a rough estimate based on this reconnaissance effort is that up to 50% of the 400,000 residents of the Municipality of Anchorage and the Mat-Su Borough live or work in nonengineered or potentially poorly-built buildings.

11.3.2 Structural Damage Patterns

- Structural damage in buildings due to the November 2018 Anchorage earthquake ranged from light cracking in most cases to major damage and partial collapse in a few cases, mainly in nonengineered and poorly detailed buildings.
- The most serious structural damage occurred in nonengineered buildings, existing buildings constructed prior to the 1990s, and buildings lacking soil reports and soil improvement. The most serious structural damage patterns observed were CMU wall-to-wall and wall-to-floor connection failure leading to roof partial collapse, wall failure in nonengineered wood buildings, and geotechnical-related structural damage due to uncompacted fills.
- New concrete buildings performed relatively well during the earthquake. Older concrete buildings had light structural damage in the form of structural wall shear cracks, flexural and splitting cracks in columns, precast connection cracks, girder minor flexural and shear cracks, and slab flexural cracking. Concrete stairs crushing and flexural cracks occurred in several cases. Concrete foundation cracks appeared in several cases because of geotechnical failures. In a few cases, concrete shear cracks were concerning in shear walls and transfer girders because of increasing width with aftershocks. No pre-1980 nonductile detail-related failure was observed. However, it should be noted that most of the inspections did not include exposing susceptible structural elements, such as lightly confined columns and unreinforced beam-column joints, so the possibility of hidden damage exists. Fiber-reinforced polymers (FRP) retrofitted concrete buildings performed satisfactorily, with little evidence of FRP debonding, except for a few isolated cracks in unretrofitted columns and walls in FRP-retrofitted buildings. It should be also noted that non-ductile concrete can deceptively exhibit satisfactory performance during modest levels of shaking; while posing the greatest damage and collapse risk at strong shaking.
- The damage observed in CMU wall buildings was especially remarkable. CMU construction has been popular since the 1960s in Alaska for many buildings, including schools, low-rise office buildings, retail and commercial buildings, sport facilities, and warehouses. Widespread CMU wall damage occurred, ranging from minor cracking to major wall instability reaching the onset of collapse. The damage in CMU walls and connections occurred even in relatively new CMU buildings. The most common CMU damage patterns observed were

connection failure between CMU wall and floor, floor joist/beam unseating off CMU, and CMU wall-to-wall connection failure. Many examples of such damage across both Anchorage and the Mat-Su Borough indicate the special vulnerability of CMU connections. Many of the buildings that experienced this damage were built after 1985, presuming seismic details were in effect. Several root causes might have led to CMU wall-floor connection seismic vulnerability, including poor design and detailing deviating from codes, poor construction of the connection details (both causes were evident in multiple buildings, including schools), the absence of positive reinforcement, or the absence of seismic details altogether. Many of the CMU walls with this type of damage warranted immediate red tagging because of significant instability concerns in floor and out-of-plane deformation of the wall, especially with a large number of significant aftershocks.

- Other common damage patterns in CMU walls were the stepped-type diagonal cracking; masonry units crushing at wall base, corners, and connections; and CMU wall-column interface detachment. The lack of connection between the ductile steel framing and CMU walls led to deformation compatibility issues and damage at the wall-frame interface. Dislodging and falling CMU blocks represented a serious life-safety hazard, as they fell from large heights. Other less common CMU failures included CMU and masonry chimney damage and CMU block foundation failure.
- Damage of residential wood buildings, especially single-family units, varied widely based on location. Structural damage in Anchorage Bowl was much less significant than in Northern Communities, especially Eagle River, which suffered widespread structural damage because of a lack of building code enforcement, as detailed previously. The magnitude of the problem of non-engineered buildings is not precisely known; however, the substantial structural damage during the earthquake, which is a relatively short-duration deep event with a relatively smaller shaking intensity compared to the 0.5g design earthquake, based on DYFI PGA of about 0.32g, is a good indicator that a large portion of the Northern Communities' non-engineered buildings with significant vulnerabilities may be at high risk of severe seismic damage (or even collapse) during a more significant event. Because shaking was not as strong, Girdwood and Turnagain did not suffer notable structural damage in wood-frame buildings.
- In Anchorage Bowl, most of the structural damage in wood buildings was due to geotechnical problems, nonengineered attachments, such as external balcony decks, and relatively older buildings constructed prior to the 1990s, when Municipality of Anchorage began to fully enforce building codes. Modern engineered buildings after 1994 suffered only cosmetic drywall cracking in most cases. In the Mat-Su Borough, some residential wood buildings and businesses suffered significant structural damage. About 19 residential wood buildings and 4 businesses suffered major structural damage.
- Common damage patterns observed in wood buildings include crawl space post and connection damage caused by soil failure; foundation damage and differential settlement; permanent residual drift in single-story residential buildings; exterior sheathing damage; interior/partition wall movement; permanent drift of parking sheds and balcony decks and detachment from main residential structure; shear wall failure and deflections; major wall diagonal cracking indicating serious structural damage; wall foundation interface uplift, sliding, and offset; detachment at wood wall corners; and detachment of floors from exterior walls. In particular, shear walls with small aspect ratios suffered the most damage.
- The sources of structural damage observed in nonengineered and older wood buildings, especially in Northern Communities, stemmed from known deficiencies summarized as follows:
 - Absence of strapping or bolting of the superstructure to the foundation
 - Absence of blockings in floor joists
 - Under-design/insufficiency of floor joists
 - Uncompacted or poorly compacted fills, leading to differential settlement
 - Absence of shear walls
 - Absence of shear wall nailing or using cheap insufficient nailing or staples
 - Under-designed or undesigned shear walls in wall thickness and/or nailing
 - Splitting and separation of sill plates
 - Crawl space connection problems
 - Absence of defined shear walls to enable installing large windows
 - Absence of defined fasteners
 - Absence of tie-backs for ledgers
 - Tall foundation walls without restraint

- Variable-height unsupported foundation posts on steep grade parcels
 - Buildings on hills and slopes were not designed for their geometry (hill building problems)
 - Extensive use of staples instead of nailing throughout entire building
 - Absence of bracing walls to detached garages
- From a structural damage viewpoint, steel buildings performed the best during the November 2018 Earthquake. A common damage pattern was damage from a connection to brittle material, such as the unseating of a steel floor joist, beam, or truss off a concrete or CMU wall or CMU or other wall infills not attached to structural steel columns leading to deformation incompatibility, damaging the brittle material at the interface. However, no confirmed structural steel damage could be reported even in pre-Northridge earthquake steel buildings. However, it should be noted that most of the inspections did not include exposing susceptible structural elements or welds, so the possibility of hidden damage exists.

11.3.3 Instrumented Buildings Lessons

- Seven instrumented buildings in Anchorage experienced light to moderate nonstructural damage and minor structural damage. All ground motion spectra recorded at the instrumented buildings were smaller than the design spectra. All buildings responded almost linearly.
- The recorded PGAs for the Atwood Building, Frontier Building, British Petroleum (BP) Building, University of Alaska's Engineering and Industry Building (EIB), and Hilton Tower were 0.21g, 0.19g, 0.20g, 0.21g, and 0.21g, respectively, while the maximum roof accelerations were 0.44g, 0.22g, not applicable, 0.58g, and 0.65g, respectively. The interstory drift ratio was estimated as less than 0.4% in an average manner by linear interpolation from roof drift by Celebi (2020) for several instrumented buildings.
- Atwood Building, a pre-Northridge steel moment frame building with a central steel shear wall core, did not have any visible structural damage. However, it experienced water damage and ceiling damage at one floor because of a piping connection failure in the mechanical room and suspended ceiling failure at three floors. A structural health monitoring model analysis of Atwood Building using the November 2018 Earthquake record by Muin, Mosalam, and Hassan (2018) based on the cumulative absolute velocity method developed by Muin and Mosalam (2017) was able to successfully predict nonstructural damage at three floors, matching the observed damage.
- The Frontier Building experienced light nonstructural ceiling and partition wall sheetrock damage and elevator counterweight damage with no water damage. The building experienced minor vertical splitting cracks in the concrete cover of many exterior and corner columns at floors 3 to 5 likely because of axial seismic overturning loads.
- The BP Tower experienced cosmetic nonstructural damage, water flooding, and some structural damage to staircases. However, the main structural elements did not experience any damage. Staircases in the main tower had minor concrete cracking and some spalling and crushing in the corners in addition to moderate sheetrock damage.
- The VA Hospital experienced only cosmetic and light nonstructural damage throughout the building but some heavier ceiling grid and tile damage on the second floor ceiling.

11.3.4 Recommendations for Seismic Risk Mitigation in Alaska

11.3.4.1 Short-Term Needs

The Alaska State Seismic Hazards Safety Commission, or other policy bodies at the State and municipal/borough level, should consider policy changes based on the results of this study. Mitigation measures that would help mitigate the seismic risk in Alaska are listed in this section.

A. New Construction and Upgrades

- Immediate state legislation is needed to prescribe a mandatory building permitting process, engineering design and plan review, and construction inspection throughout Alaska, including all the communities and unincorporated areas outside the current jurisdiction of the Municipality of Anchorage ABSSA. This should apply to any new construction, building addition, or upgrade. The State of Alaska is encouraged to follow other states' experiences in this regard. For example, the State of Washington State Building Code Act (RCW 19.27): "Adoption of building codes initially was the discretion of individual cities and counties.

Passage of the State Building Code Act in 1974 mandated the use of 1973 UBC building codes throughout the state. Since this time, local jurisdictions can make amendments to the code but changes cannot diminish code requirements.”

- An immediate change in the existing Anchorage building code is needed to require building upgrades to conform to the most recent International Building Code (IBC 2018) as a condition to issue permits for any building addition or upgrade.
- Geotechnical reports and soil improvement as needed should be integral requirements of the permit documents for all new construction, building additions and applicable upgrades.

B. Existing No-Permit/Nonengineered/Noninspected Publicly Accessible Buildings

- Nonengineered buildings that are accessible to the public constitute significant public safety hazards in the event of earthquakes, even if privately owned. Customers and building users assume such buildings are earthquake-resistant and further assume it is the role of the state to ensure occupants are safe when they use such buildings.
- An immediate state legislature bill/ordinance is needed to require and enforce a structural/seismic safety screening/assessment and retrofit of all nonengineered buildings accessible to the public and found to pose a life safety risk. The program may need to be phased, or alternatively, conducted at Borough/Municipality level. This screening/assessment can be tiered using FEMA P-154 and ASCE 41-17 seismic assessment methodologies or similar. Building owners should bear the cost of Tier 1 and Tier 2 assessments. Structures that trigger Tier 3 seismic assessment can be partially subsidized by state or federal assistance. The ordinance should require seismic retrofit of those buildings that pose seismic collapse risk. State or federal subsidies, or tax incentives, should be considered to motivate owners to retrofit their buildings. For the short term, owners who refuse to retrofit their buildings shall post a mandatory visible sign warning building users of the high seismic collapse risk of their buildings and advising to use at own risk.
- Within 1 year of the ordinance, building owners should submit an assessment report showing adequate seismic capacity or retrofit or demolition plan timeline.

C. Existing No-Permit/Nonengineered/Noninspected or Older Engineered Family Housing

- For any nonengineered houses or for engineered houses built prior to UBC 1979, the state should encourage using homeowner seismic safety guides, such as FEMA 530 or similar seismic safety brief checklists, for self-assessment of seismic hazards. This should be done through public awareness, outreach, media campaigns, and education and availing municipal resources to conduct this type of assessment upon building owner's request.
- Seismic safety of deficient single-family wood buildings can be significantly improved using simple inexpensive retrofit measures. The municipalities should facilitate issuing expedited permits for these retrofit measures and should inspect their construction.
- State and federal subsidies toward the cost of these simple retrofit measures can be provided as well as tax relief upon building owner's request.
- Dispensing federal and state earthquake assistance could be tied to retrofitting buildings..

D. Existing Pre-UBC 1997 Older Engineered Essential Facilities and “Alaska Critical Infrastructure”

- The State of Alaska currently has only three general legislations regarding seismic hazard mitigation. These do not include hazard mitigation in existing structures vulnerable to seismic collapse during strong shaking. For reference, 80% of Anchorage Bowl building stock was constructed before 1997.
- The State needs to make informed decisions in emergency planning and loss scenarios under the MCE, considering the current seismic vulnerability of essential/emergency facilities and publicly owned older buildings that were designed with obsolete codes predating the Northridge earthquake. Many of these buildings may pose significant seismic collapse risk with high human and economic losses. Types of structural deficiencies in these buildings may include but are not limited to nonductile concrete, nonductile CMU, deficient pre-Northridge welding in steel buildings, unreinforced masonry (URM), soft and weak story buildings, and buildings with other structural irregularities. These structures include all “Alaska Critical Infrastructure” as defined by the State of Alaska Hazard Mitigation Plan, including K-12 public school buildings and educational facilities, hospital buildings with acute care units, fire and police stations, law enforcement agency buildings, high-occupancy buildings, airport and port facilities, and buildings or other structures that can be classified as Risk Category III or IV per ASCE 7-16 definition.

- To assess seismic retrofit needs as a first step, state legislation is needed requiring rapid visual screening (RVS) of these buildings using FEMA P-154 and for those buildings failing the RVS, tiered seismic assessment using ASCE 41-17 followed by thorough assessment if needed. State-owned buildings' assessment should be funded through state or federal funds, while the assessment of privately owned buildings that fall into this category should be performed at the owner's expense, subsidized with state or federal funds as needed.
- The State is encouraged to follow other states' experience in updating seismic risk mitigation policy for this class of buildings. The State of Oregon passed a bill in 2005 to develop Statewide Seismic Needs Assessment Using Rapid Visual Screening (RVS) [Senate Bill 2 (2005)]. Oregon also passed companion bills to establish and fund seismic rehabilitation grants [Senate Bills 3, 4, and 5 (2005)]. The State of California Earthquake Safety and Public Buildings Rehabilitation Bond Act was passed in 1990 (Prop. 122 and Government Code §§ 8878.50-8878.52) after the 1989 Loma Prieta earthquake revealed vulnerabilities to state-owned and essential services buildings.
- The State is also encouraged to consult policy recommendations by Western States Seismic Policy Council (WSSPC), EERI, National Earthquake Hazard Reduction Program (NEHRP), and FEMA in drafting its prospective revised seismic risk mitigation legislation.

E. Existing Older Seismically Vulnerable Engineered Private Buildings

- Pre-UBC 1979 existing "older" buildings (and Pre-UBC 1997 steel buildings) engineered to outdated building codes may pose substantial seismic collapse risk during strong shaking because of structural deficiencies that were not recognized in these building codes because of a lack of knowledge. These buildings include all types of private buildings not outlined in Section D above, including residential, commercial, and office buildings. Researchers and engineers learned about the high seismic risk due to these deficiencies after observing major human and economic losses in strong past earthquakes such as Alaska 1964, San Fernando 1971, Loma Prieta 1989, Northridge 1994, and Kobe 1995. Lessons learned from these events led to major changes in building codes in 1976, 1979, 1994, and 1997 to avoid these structural deficiencies and provide appropriate seismic details for acceptable "Life Safety" performance during strong shaking. These structural deficiencies include but are not limited to nonductile concrete, nonductile CMU, deficient pre-Northridge welding in steel buildings, URM, soft and weak story buildings, gravity system seismic detailing, and buildings with structural irregularities.
- The State of Alaska and/or local jurisdictions are urged to issue a bill/ordinance to enforce seismic assessment and retrofit of building types that pose the greatest risk to the public. The State/City Councils are encouraged to follow the example of the City of Los Angeles, which, despite its lower seismic hazard compared to the Anchorage Bowl, issued the 2015 Ordinance No. 183893 to enforce seismic assessment and retrofit of all its pre-1978 15,000 wood-frame soft story buildings and 1,500 nonductile concrete buildings. The City of Santa Monica has followed with a similar ordinance in 2017, and other cities on the West Coast are underway in issuing similar ordinances. The seismic assessment should be performed at the building owner's expense with state and federal subsidies as needed.
- Within 2 years of the ordinance, building owners should submit an assessment report showing adequate seismic capacity or retrofit or demolition plans.

11.3.4.2 Long-Term Needs

The following long-term recommendations to reduce seismic collapse risk in vulnerable buildings in Alaska are suggested via state legislature, enforcement, and implementation of the relevant short-term needs outlined previously by the following suggested dates:

A. New Construction and Upgrades

- All new construction, building additions, and upgrades in Alaska must follow IBC 2021 and its Alaska amendments by 2022. State and city councils and communities are encouraged to utilize the new FEMA Building Resilient Infrastructure and Communities (BRIC) program to help regulate the newly proposed state legislation.

B. Existing No-Permit/Nonengineered/Noninspected Publicly Accessible Buildings

- Tax incentives, state and federal assistance programs, the FEMA BRIC program, a special seismic retrofit grant (similar to Oregon's grant), or funding through permit fees or real estate resale registration fees can be established to provide partial subsidy for long-term retrofit plans of these buildings.
- By 2028, all seismic retrofits or demolition of such buildings should be completed.

C. Existing No-Permit/Nonengineered/Noninspected or Older Engineered Family Housing

- State legislation bill/ordinance to enforce seismic assessment and retrofit of this class of building should be issued by 2023.
- By 2025, all building owners should submit structural plans, recent as-built inspection reports showing adequate seismic capacity, or seismic retrofit or demolition plans.
- Tax incentives, state and federal assistance programs, the FEMA BRIC program, a special seismic retrofit grant (similar to Oregon's grant), or funding through permit fees or real estate resale registration fees can be established to provide partial subsidy for long-term retrofit plans of these buildings.
- By 2033, all seismic retrofits or demolitions of such buildings should be completed.

D. Existing Pre-UBC 1997 Older Engineered Essential Facilities and "Alaska Critical Infrastructure"

- After assessing seismic retrofit needs as outlined in the short-term recommendations, a tailored state seismic retrofit plan that prioritizes retrofit needs based on seismic risk, budget, and impact of building failure during an earthquake should be implemented.
- Funding via state and federal grants, FEMA BRIC, and/or special seismic retrofit grant should be provided to retrofit public and state-owned buildings and partially subsidize retrofitting private buildings of high occupancy or Risk Category III and IV.
- The seismic retrofit plan can be implemented incrementally based on available budget over the period of 2022-2035. An example of an incremental seismic retrofit plan can be found in FEMA 395, Incremental Seismic Rehabilitation of School Buildings (K-12).
- By 2030, all such facilities should be retrofitted to achieve life safety performance, or have the use changed so that the building is no longer an essential facility or Alaska Critical Infrastructure.

E. Existing/Older Seismically Vulnerable Engineered Private Buildings

- Based on the State of Alaska/City Councils—issued a bill/ordinance to enforce seismic assessment and retrofit of these buildings (pre- UBC 1979 buildings and pre- UBC 1997 steel buildings), as outlined in the short-term recommendations, a seismic retrofit plan should be implemented.
- Tax incentives, state and federal assistance programs, the FEMA BRIC program, a special seismic retrofit grant (similar to Oregon's grant), or funding through permit fees or real estate resale registration fees can be established to provide partial subsidy for long-term retrofit plans of these buildings.
- The 80 percentile most vulnerable buildings of this category shall be seismically retrofitted or demolished by 2030.

11.4 Nonstructural Damage Lessons

- Widespread nonstructural damage was observed from the November 2018 earthquake. The most common nonstructural damage observed, and the most disrupting to building function and costly to repair, was the water flooding caused by fire-suppression system failure, water boiler rigid piping failure caused by unanchored boiler sliding, and mechanical room water and glycol piping and connections failure.
- Other common nonstructural damage patterns observed were glass façade and window failure in low-rise buildings, suspended ceiling tile and grid failure in office and commercial buildings, extensive sheetrock/drywall cracking in all types of buildings, especially at stairwells, and overturning of tall furniture items.
- Less common nonstructural damage patterns observed were masonry veneer cracking and failure, partition wall damage ranging from light cracking to out-of-plane deformation and complete detachment from building, mechanical equipment and HVAC ducts failure caused by poor restraint, internal boiler cracking, electric hardware failure caused by water damage, and gas leaks caused by connection failures of rigid gas pipes.
- The main reasons/lessons identified for firefighting system failures are as follows:
 - Rigidly connected sprinkler head collision with other systems or with drop ceiling
 - Poorly restrained rigid piping connection/fitting failure
 - Collision of firefighting piping system with orthogonal/different plane systems

- Obsolete codes and lack of code enforcement were contributing factors in poor performance. Buildings constructed after 2003 exhibited good firefighting system seismic performance.
- Long vertical wire ceilings and cloud ceilings especially performed poorly.
- Flexible piping sprinkler systems performed satisfactorily.
- The main observations/lessons from water heater/mechanical room water damage are as follows:
 - Seismically unrestrained (or poorly restrained) water boilers/heaters failure of connections to rigid pipes. Unrestrained heaters existed in nonengineered/noninspected buildings or in the case of a large-size boiler not requiring seismic restraint by code.
 - ASCE 7 requires piping connections to allow for several inches of movement in the case of unrestrained tanks, but owners of unrestrained boilers failed to meet this requirement in most cases.
 - Some unrestrained tanks with flexible piping also exhibited connection failures caused by large displacement. It seems that a code language change and/or a new seismic restraining provision against sliding of all water boilers are warranted.
 - Lack of code enforcement was the reason for many heater connection failures.
 - Internal cracks of water boilers occurred in several cases, causing water leakage.
 - Mechanical room piping failure of rigid glycol pipes/connections/pumps of the heater system, especially at the interface of heavy HVAC equipment
 - The absence of an emergency plan in many buildings that tackles emergency shutting off water after an earthquake was key in exacerbating water damage.
- The main equipment damage observations/lessons identified are as follows:
 - Movement of seismically unrestrained (or poorly restrained) heavy equipment caused damage to connected pipes, ducts, and other systems.
 - Flexible restraint/strapping performed better than rigid restraint of equipment.
 - Counterweight dislodging or damage in elevators causing operation disruption was common.
 - Vibration isolators suffered damage because of poor anchorage or lack of anchorage.
 - Pump failure was observed in a few cases.
 - HVAC systems suffered extensive damage in older/nonengineered buildings with poor seismic restraints. The main damage was at duct connections. Duct flange damage and Variable Air Volume (VAV) box and duct damage were common during the earthquake.
 - Permanent residual rotation/displacement was observed in rigid ducts covering large spans such as gymnasiums or basketball courts.
 - HVAC system insufficiency was reported following restoration of service and repairs. This might be attributed to out-of-balance internal mechanical parts or air duct leakage caused by unobserved cracks at connections.
 - New seismic gas valves were efficient for shutting off gas during the earthquake and preventing building damage.
 - Heavy electrical equipment, such as data and telecommunication towers, were not seismically restrained and slid or overturned during the earthquake.
 - Some electric panel housings were damaged and detached, and electric panels suffered short circuit damage because of water leaks.
- The main observed patterns/lessons from nonstructural ceiling damage are as follows:
 - Damage to suspended grid ceilings was extensive in many buildings in Eagle River, Anchorage, and Mat-Su,
 - In most cases with ceiling grid damage, the grid wire spacing was insufficient and nonconforming to code requirements, especially in older buildings.
 - Ceilings of post-2000 buildings performed better than older buildings.
 - Suspended grid direct ceiling damage was more pronounced in low-rise buildings (1-2 stories) than mid-rise and high-rise buildings.
 - Grid ceiling damage was significantly more pronounced in low-rise buildings in Eagle River compared with Anchorage Bowl.
 - Ceiling damage to stiff low-rise buildings was much more pronounced than that in flexible low-rise buildings.
 - Sprinkler heads were the main source of ceiling tile damage.
 - Schools, hospitals, and low-rise commercial and office buildings particularly suffered intense ceiling damage.

- Heavy wooden ceiling tiles fell in many buildings, even the newly constructed ones. Heavy tiles falling from large heights are life-safety hazards. Some building owners switched to light Styrofoam tiles or no suspended ceilings as a result.
- The main observed patterns/lessons from veneer, façade, partition, and nonstructural wall damage are as follows:
 - Veneer, window, and façade damage was more significant in low-rise buildings than in mid-rise and high-rise buildings. Damage of these components in Eagle River was much more significant than in Anchorage and Mat-Su.
 - Typical gypsum, concrete, brick, and stone veneer damage, especially at corners and around openings, was observed.
 - Damage to windows in commercial buildings was extensive in Eagle River and moderate in Anchorage.
 - Although estimated drift exceeded code limit for glass shattering in many mid-rise and high-rise buildings, glass was intact except in rare cases.
 - Extensive damage was observed to nonstructural partition walls because of the earthquake. The sheetrock/drywall damage was the most commonly visible damage in all types of structures, especially at stairwells.
 - Nonstructural partition wall damage ranged from cosmetic to extensive. Even in those buildings receiving less than 0.2g PGA, sheetrock damage was widespread.
 - Aftershocks have exacerbated the sheetrock damage problems in the region.
 - The cost of repair of this type of crack can be relatively high, especially with stairwells needing scaffolding.
 - Many building owners will not repair the partition wall damage because of high cost/possibility of future aftershocks and earthquakes.
 - More ductile partition wall finishing material might be needed in an active seismic region like Alaska.

11.5 Performance of Schools

11.5.1 Concluding Remarks

- Both Anchorage and Mat-Su schools in areas of stronger shaking performed well structurally, with three notable exceptions. These three schools were red-tagged and closed for the remainder of the year. Because of a combination of moderate shaking and students fortunately not being present in areas with falling block masonry, these schools were life safe, with all students able to exit buildings safely. This may not be the case in future stronger earthquakes, however, so more must be done to address vulnerable school buildings before the next earthquake strikes. Both school districts had done some seismic assessments of schools, which indicated additional vulnerabilities that need to be addressed. Both districts had done some seismic upgrades as part of remodeling, reroofing, or other projects but had not yet been able to retrofit or replace all vulnerable school buildings. For decades, new schools in both districts have been designed to current codes for locations with high seismic hazard and, since approximately the early 1990s, with more rigorous plan check and construction supervision by the district and municipality or borough. This ongoing commitment to building seismically safe schools is evident in the overall performance of schools at the portfolio level.
- Many schools suffered significant damage to architectural elements—particularly suspended ceilings—as well as to HVAC systems, piping, and other building systems, which caused significant school disruptions and closures. Both districts had a practice of anchoring shelving and other heavy classroom furnishings, and almost all furniture was anchored, which undoubtedly helped to protect students. Because of the variation in school ages, both districts had schools that completely lacked seismic anchoring or bracing for architectural elements, equipment, and building systems as well as schools in which all these were anchored in accordance with modern code provisions. As expected in such a situation, schools experienced a spectrum of nonstructural damage ranging from minor to severe. Intensive and remarkable efforts by the facilities staff in both districts were necessary to repair and clean up this damage so that schools could resume instruction, which took place within 2 weeks, with students at the closed schools shifted to other locations. Mat-Su schools with severe nonstructural damage caused by a lack of seismic anchoring and bracing were closed significantly longer than those schools with minimal nonstructural damage.
- Both districts had preparedness programs in place. These included earthquake drills at least twice per year, in which students practiced “Drop, Cover, and Hold On” under their desks. Such drills were shown to be effective in middle and high schools that were in session during the earthquake; students immediately took

cover under desks. In schools that had severe damage to ceilings and lights, this certainly reduced the number of injuries. The combination of life-safety structural performance in most cases, anchoring of heavy furnishings, and student preparedness and drills to practice protective action appears to have protected students and staff. Despite significant damage, very few injuries occurred: 16 student injuries and 13 staff injuries.

11.5.2 Lessons Learned

As the strongest U.S. earthquake in many years to strike while schools were in session, this event provided several important lessons, both for Alaska schools and schools elsewhere:

- Structural damage to schools in this event is a reminder that remaining older schools must be seismically evaluated and strengthened or replaced if needed. Tools such as FEMA P-154 RVS and ASCE 41 Tier 1 assessments can start the assessment process cost-effectively.
- If districts want to reduce lost instructional time and prevent injuries in future earthquakes, more attention must be paid to ensure that nonstructural components have adequate seismic design. The majority of damage and most injuries were due to nonstructural failures.
- Nonstructural damage during earthquake shaking even below 60% of the design-based earthquake may not be “Life Safe.” Examples are CMU blocks dislodged from partitions and heavy ceiling tiles falling from high elevations.
- Investing in seismically safe schools, both through ensuring new schools are built to current seismic codes and assessing and strengthening older schools, reduces damage and downtime and protects students;
- It is recommended that the State considers seismically upgrading all older schools built prior to IBC-2000.
- Seismically upgrading pre-UBC 1979 schools and pre-UBC 1997 steel frame system schools is an essential seismic safety priority to avoid catastrophic losses during future strong earthquakes.
- Anchoring heavy shelving and furnishings protects students and staff and should be required in all schools, along with education for teachers that furniture that is moved must be re-anchored to protect students; both districts reported that teachers frequently wanted to move furniture and that it was a challenge to keep everything anchored. This earthquake shows that those extra efforts to ensure furnishings are essential and worth doing.
- All schools should have preparedness programs, tested with drills, which include instruction on what to do during shaking if students are in classrooms or other locations. Student-protective actions prevented many injuries in schools in which severe ceiling damage occurred, with tiles, light fixtures, and air diffusers falling, and where contents spilled from shelving.
- Experiences in this earthquake show that school earthquake safety and preparedness programs work. Despite both districts being “mid-program” on reducing the risk from their older schools and having more work to do, the substantial progress already made toward earthquake safety is notable and provides an example for other districts elsewhere.

11.6 Performance of Hospitals

11.6.1 Damage Observations

- The three major hospitals in Anchorage had light-to-heavy nonstructural damage, several water leaks and flooding, and some equipment damage, although emergency rooms remained open, except for one that was closed briefly to repair water damage. Minor structural damage occurred in hospitals. All three hospitals canceled elective surgeries and noncritical appointments.
- Alaska Regional Hospital experienced the most visible damage with water flooding that affected large segments of floors and ceilings because of a firefighting system failure that led to nearly shutting down two outpatient clinic buildings on campus, which partially resumed operation with an estimated 20-30% capacity 2 weeks after the earthquake.
- One of the three major Anchorage hospitals experienced many structural core wall shear cracks in its pre-1980 building.
- At another Anchorage hospital, major penthouse mechanical room boiler failure occurred, leading to building flooding, electric panel failure caused by a short circuit, and a consequent fire alarm activation. The same hospital experienced major geotechnical soil failure that affected the hospital floors and exteriors.

- The Mat-Su Regional Medical Center remained open but experienced minor structural damage, glycol leaks leading to a shutdown of the heating system, and some piping failure caused by water tank sliding, along with other minor nonstructural damage. A gas line break, resulting from an unanchored boiler in the mechanical penthouse of an adjoining medical office building, caused the building to be evacuated (the hospital itself was not evacuated), and the office building also suffered significant water damage from leaking pipes. The VA Hospital experienced some cosmetic sheetrock cracking and some ceiling damage at the second floor only and remained operational.
- Elevator counterweight dislodging and damage that disrupted service was common in many hospitals and health care facilities.
- The main blood bank facility in Anchorage experienced major nonstructural damage and water flooding and some structural damage and was out of service for 1 day only following the earthquake.
- Many outpatient clinics and health care facilities experienced typical office building damage, including water flooding. Many of these facilities were out of service for a few days/weeks following the earthquake.
- Overall, the hospitals' performance was acceptable in both Anchorage and the Mat-Su Borough, but this should be viewed in light of the relatively small-to-moderate shaking intensity recorded near hospital locations (0.14g to 0.32g), which has probably led to less than 50% of design basis earthquake shaking.

11.6.2 Lessons Learned and Improvement Recommendations

- Nonstructural damage was the most disruptive to hospital operation, with the highest cost to repair.
- Failure of firefighting system hardware and mechanical room piping causing major water flooding were the most disruptive and costly nonstructural damage in hospitals.
- Serious structural damage in older hospital buildings might be a concern during an MCE scenario.
- Good seismic retrofit programs and paying attention to nonstructural components' up-to-date construction minimized the cost of repair following earthquakes.
- The Southcentral Alaska has a limited number of emergency rooms at hospitals. Functionality of all emergency rooms immediately after an MCE event is a concern. Major disruption of one or more emergency rooms is possible because of severe nonstructural damage.
- At the time of this report, follow-up hospital impact surveys are still needed to be performed to capture lessons from the health system's response to the earthquake. Furthermore, epidemiology studies investigating causes of injuries would be a valuable addition to existing studies from past earthquakes on injuries, protective actions taken during earthquakes, and interior environments.
- At the time of this report, interviews of hospital personnel does not imply the presence of full-functioning post-earthquake response plans that include detailed written procedures on the roles of each employee or the lead-person approach followed in many other seismic-prone regions. The example of Chile's hospitals' earthquake and tsunami response procedure is recommended for Alaska hospitals.
- Backup communication plans that assume total loss of telecommunication networks do not seem to be in place in all three major hospitals in Anchorage. These backup plans are much needed to coordinate patient and emergency supplies' transport between the three major hospitals and to coordinate locating and transporting health care professionals between the three hospitals. Alternative communication means, including off-line mobile apps, emergency satellite phones, and long-range radio communications, are recommended for such plans for Alaska hospitals.
- Since the Mat-Su Regional Medical Center does not enjoy redundancy within its vicinity, a post-earthquake communication and patient and medical supply transport plans should be in place assuming collapse of several segments of the only artery that connects Mat-Su Valley to Anchorage hospitals: the Glenn Highway. These plans should consider air ambulance scenarios and capacities. Similar scenarios should be investigated for Eagle River and Northern Communities with especially high vulnerability to serious injuries and fatalities following a major event, with the possibility of collapsed portion(s) of the Glenn Highway, their only route to Anchorage.
- It is noteworthy that all the aforementioned recommended hospital response plans should consider severe weather conditions in the winter. The readers are referred to NIST Special Publication 1224, Research Needs to Support Immediate Occupancy Building Performance Objective Following Natural Hazard Events, for further details regarding performance of hospitals in major earthquake events. The readers are also encouraged to consult Oregon Resilience Plan 2013, several FEMA hospital earthquake safety guides, and California Office of Statewide Health Planning and Development (OSHPD) guides.

11.7 Bridges and Transportation System

11.7.1 Bridge Damage Observations

- The 2018 Federal Highway Administration National Bridge Inventory classifies 9.7% (155 bridges) of the state's bridge inventory as structurally deficient. 12 of the deficient bridges are on the interstate Highway System. Of the deficient bridges, five aging bridges (older than 50 years) are located in Anchorage Metro and are considered heavily travelled.
- The observed bridge structural damage to the region's inventory of 243 bridges was generally minor and mostly related to geotechnical failure.
- Twenty bridges had more significant structural damage needing permanent repairs to be conducted in 2020.
- Commonly found structural damage was girder shifting, shear key cracking, light-to-severe cover spalling and damage of shear keys exposing reinforcement, bent anchor bolts, bearing large deformation, damage of grout pads under bearings, pile cap concrete spalling, wing and hider wall cracks, and bridge transverse and longitudinal permanent displacement and misalignment.
- Structural and foundation damage caused by ground failure was common. This was manifested in abutment cracks, approach settlement, settlement of abutments, wing wall settlement, soil cracks, hider wall cracks, culvert failure, rail misalignment, and slope tension cracks.
- The Alaska Department of Transportation and Public Facilities bridges' fundamental periods range from 1.5 to 3.5 seconds. Recorded ground acceleration was about 30% of the design earthquake acceleration for this period range, so all bridges responded elastically.

11.7.2 Road Damage Observations

- The November 2018 earthquake caused widespread damage to roads and highways. Detailed information on road damage was provided in Chapter 8.
- Fifty-eight locations of damage on the road system were identified in the region, with eight locations identified to have the most severe damage.
- Liquefaction-induced settlement of roadways was not common but did occur in parts of Anchorage and outlying areas.
- Several significant slope failures occurred as a result of the earthquake. Major slope failures from the 1964 Great Alaska Earthquake did not remobilize, perhaps because of the short duration of strong shaking.
- Several other slope failures were observed and documented. Notable slope failures included the slope near Milepost 24 on the Glenn Highway near Mirror Lake, Milepost 50 of the Seward Highway, and slopes near the Alaska Railroad Corporation tracks near Rabbit Creek in South Anchorage.
- As spring thawed out the frozen soils, there were several embankments that slumped, causing pavement damage and roadway settlement.
- Some of the most severe failures observed consisted of native foundation soils that failed below fill soils. Two examples that received national and international attention are the Minnesota Drive northbound off-ramp at International Airport Road in Anchorage and Vine Road in Wasilla.
- The initial failure mode in Minnesota Drive is global rotational slope failure caused by low shear strength saturated sandy silt soils unable to resist the driving forces of the roadway embankment fill above.
- The failure at Vine Road, which crosses deep muskeg, is likely again due to global rotational slope failure caused by saturated low shear strength peats supporting the road embankment.

11.7.3 Transportation System Resilience

- All essential travel routes were restored by December 5, five days after the earthquake.
- Approximately 150 sites were identified that need permanent repairs, and it is anticipated that this may take multiple years to complete.
- The observed damage did not cause closure of any bridges for structural repair.
- Temporary repairs of the 20 bridges with more significant structural damage were performed in the first 5 days after the earthquake. Permanent repairs of these bridges are planned to be performed in 2020.
- Some bridges were closed because of road approach failure and reopened as outlined in Chapter 8.

11.7.4 Recommendations to Improve Transportation Seismic Safety and Resilience

- The State should invest in seismically upgrading critical and aging road and bridge facilities in Southcentral Alaska, prioritizing the seismic retrofit based on seismic risk, budget, and projected impacts on economy and population by losing each transportation facility during a major MCE event.
- Uncompacted and poorly compacted fill problems under highways and bridges should be identified and soil improvement projects should be pursued to reduce seismic geotechnical failure risks.
- The State needs to make informed decisions in emergency planning and loss scenarios under the MCE about the current seismic vulnerability of essential and critical roads and bridges that were designed with obsolete codes.
- The State is encouraged to follow other states' experience in updating seismic risk mitigation policy for its transportation infrastructures.
- The State is also encouraged to consult policy recommendations by WSSPC, EERI, NEHRP, and FEMA in drafting its prospective revised seismic risk mitigation legislation.
- The seismic retrofit plan can be implemented incrementally based on available budget over the period of 2021-2035. An example of incremental seismic retrofit plan can be found in FEMA 395, Incremental Seismic Rehabilitation of School Buildings (K-12).
- By 2030, all such transportation facilities in Southcentral Alaska should be upgraded to an appropriate level of seismic performance.
- Transportation system redundancy is a critical need for some parts of Southcentral Alaska. An example is Anchorage's Northern Communities of some 30,000 residents and nonengineered building stock that can be especially vulnerable to serious injuries and collapses during an MCE event. These communities are connected to Anchorage's and Mat-Su's hospitals and trauma centers with only one accessible route, which is Glenn Highway. Should a portion or more of the highway collapse during an MCE event, only air transport can service these communities. It is suggested to have realistic air transport scenarios for the injured, deployable bridge scenarios, and/or to build a parallel local road collateral/bypass to the Glenn Highway in sections where such alternates do not exist or are similarly vulnerable.
- The State is encouraged to utilize high-performance bridge materials and systems in new construction that minimize seismic damage and repairs and provide excellent resiliency and operability following a major seismic event. Example materials and systems are self-centering bridge columns, base-isolated bridges, high-performance concrete bridges, and bridge columns reinforced with shape-memory alloys.

11.8 Performance of Lifelines

- The railroad suffered moderate damage, including ground cracking, north of Anchorage, causing closure of the route from Anchorage to Fairbanks.
- On December 2, all landslides on the Alaska Railroad were cleared south of Anchorage to allow the resumption of freight from Whittier to Anchorage. Following repairs, regularly scheduled freight and passenger service on the Alaska Railroad was resumed on December 4.
- Oil pipelines were briefly shutdown for inspections, but no pipeline damage was reported.
- Power outages were widespread in Anchorage and the Mat-Su Borough, but power was restored within 24 hours for most customers.
- Extensive damage to water mains was observed in the aftermath of the earthquake. Breaks in underground mains often occurred because of ground settlement. In addition to breaks in water mains, there were over 300 reported instances of water leaks in structures that required Anchorage Water and Wastewater Utility (AWWU) to turn off the water at the main. AWWU used 4 outside contractors and had crews working 24 hours a day for multiple weeks. Additional water main breaks continued to be discovered in the months following the earthquake.
- Damage to sewer systems was observed, with settlement identified as the primary cause.
- AWWU issued a water boil notice as a precautionary measure. The water boil notice was lifted at 2:00 p.m. on December 2.
- Hundreds of gas leaks were reported at residences because of rigid pipe connection failures. In many instances, hard-pipe unions needed tightening, and more routine maintenance is recommended. Damage was not observed in cases in which flexible gas piping connectors were used, and the use of flexible gas piping connectors over rigid connectors is recommended.

- Eagle River lost power following the earthquake, and fuel pumps were unavailable. It is suggested that energy companies store fuel for their vehicles at service areas.
- The Anchorage airport was open after the earthquake but was operating at reduced capacity. TSA bagging screening was not operational, causing delays to outbound flights to conduct manual baggage screening. Alaska Airlines and Delta Airlines temporarily suspended service to Anchorage, but service was restored within a few hours.
- At the Port of Alaska, significant structural damage was observed to the seams of pile welds. Damage was attributed to the welding steel used in the 1960s and 1970s, which differed from modern-day welding steel and was more corrosive than the main pile steel. After snow melted in Spring 2019, very significant pile damage that threatened structural collapse, especially under Terminal 2, was observed. Long term hidden damage monitoring plan should be implemented at the Port, especially for elements that are inaccessible during winter conditions.
- Port of Alaska nonstructural damage occurred to dock lights and cameras as well as failure of wires and connections in cathodic protection systems, in addition to nonstructural damage to buildings. Significant geotechnical failures were also observed at the Port of Alaska and included slope failures and liquefaction.

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On November 30, 2018, an M7.1 earthquake hit Southcentral Alaska. In the weeks following the earthquake, the Earthquake Engineering Research Institute (EERI) Learning from Earthquakes (LFE) Business Resilience Subcommittee monitored news reports and liaised with investigators in the field to understand the impact of the earthquake on businesses in and around Anchorage. On December 21, the subcommittee decided to deploy a small team of researchers to conduct in-person surveys of businesses, although the team did not travel to Anchorage until several months later. The field team included Mike Mieler (Co-chair of Business Resilience Subcommittee), Manny Hakhamaneshi (Co-chair of Virtual Earthquake Reconnaissance Team (VERT)), Zoe Yin and Ana Orozco (EERI), and Kai Wu (doctoral student at Texas A&M). The team received institutional review board approval for the study on January 31, 2019.

The primary objective of the deployment was to test the survey instrument developed by the subcommittee across a range of business types and damage scenarios, not to obtain a representative sample of businesses to understand the earthquake impacts across the entire Anchorage region.

Prior to deployment, EERI's VERT compiled a database and map of damaged businesses from news reports and data uploaded to the clearinghouse website. The field team used this information to identify four clusters of businesses in and around Anchorage to survey, including one cluster in Eagle River, two clusters in downtown Anchorage, and one cluster south of Anchorage. Because the VERT database focused on damaged businesses, the tables and figures in this section should not be interpreted as representative of all businesses in the Anchorage region.

The team modified the survey instrument used in the 2016 Cushing, Oklahoma, earthquake and created an electronic version in Fulcrum. The survey comprised two sections: a "business impacts" section for documenting the impact of the earthquake on business operations and an "engineering damage" section for recording structural and nonstructural damage at the business location. Each section was designed to take approximately 15–20 minutes to complete, with the engineering damage section only required if the business experienced significant building damage.

The team surveyed businesses in Anchorage and Eagle River from Saturday, March 16, through Monday, March 18, 2019. While in the field, the team split into two groups of two or three investigators and used a combination of opportunistic and snowball sampling to identify additional businesses to survey beyond those identified in the VERT database. In total, 56 unique businesses were visited over the course of 3 days, with 23 businesses completing the survey, an effective response rate of 41%. Table 1 summarizes the number of businesses visited within each of the four clusters, while Figure 1 shows a map of the businesses surveyed. The survey took between 15 and 60 minutes to complete, depending primarily on the extent of earthquake damage. Of the 33 businesses that were visited but not surveyed, only a few of them outright declined to participate in the survey. More often, the reason for not participating was the lack of a business owner or manager on site to complete the survey. When possible, the team revisited businesses when such a person would be available.

Table 1. Summary of businesses visited.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Total
Total visited	17	22	7	10	56
Completed survey	5	10	4	4	23
Response rate	29.4%	45.5%	57.1%	40.0%	41.1%

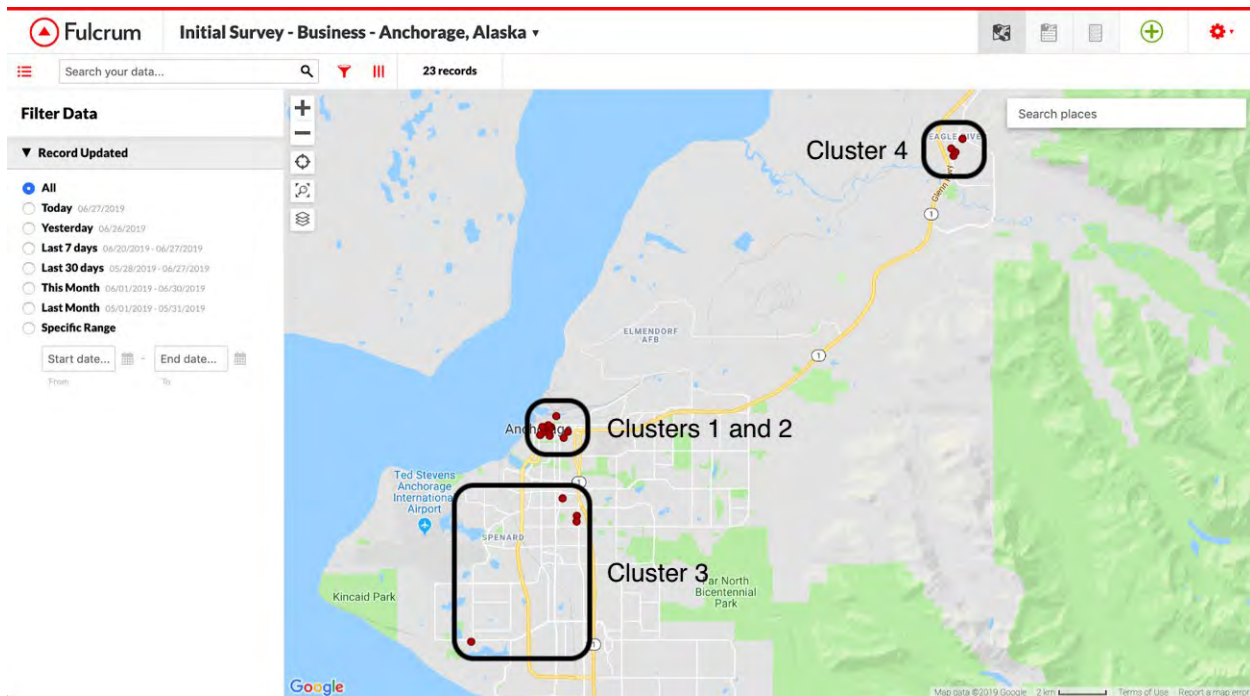


Figure 1. Map of businesses surveyed in Anchorage and Eagle River.

Most of the businesses surveyed were in the retail, food services, or hospitality sectors and ranged in size from small, independent businesses to large, national franchises and corporations. Figure 2 shows a histogram of the number of full-time employees before the earthquake for the 23 businesses surveyed, showing a wide range of sizes, from a few employees to over 100. With the exception of two businesses that were still closed at the time of the survey, none of the businesses reported significant changes to the number of employees as a result of the earthquake. Note that one of the businesses surveyed had opened since the earthquake and therefore had no full-time employees before the event, which is why the number of businesses in Figure 2 sums to only 22.

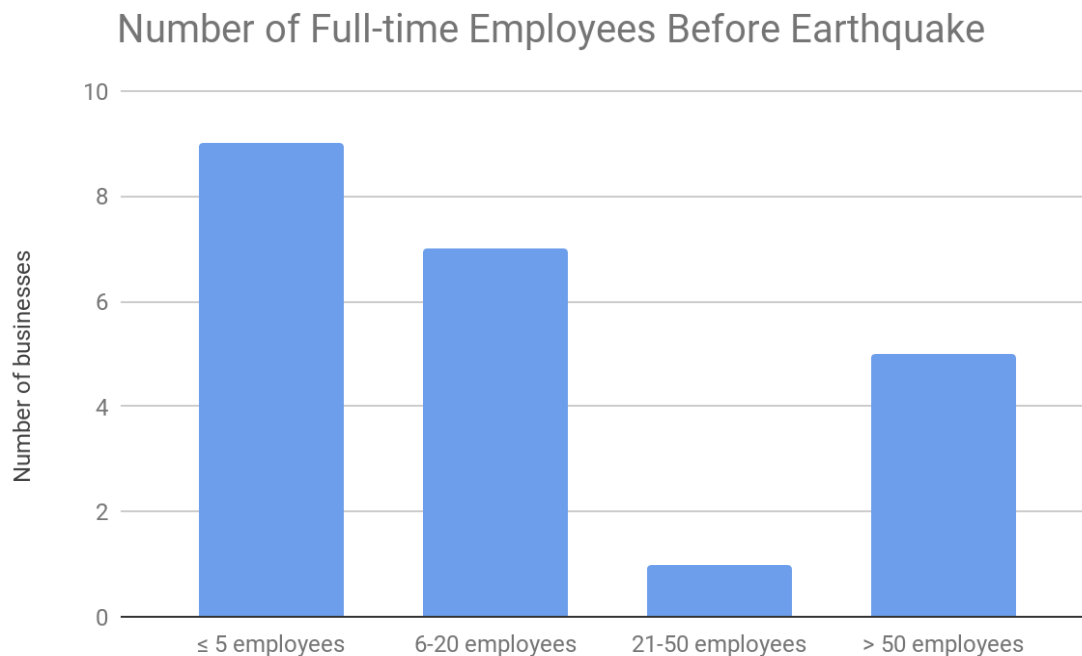


Figure 2. Size of businesses surveyed, as measured by the number of full-time employees before the earthquake. Because of the small sample size and nonrandom sampling, data are not representative of businesses in the Anchorage region.

Figure 3 shows the extent of earthquake damage to the 23 businesses surveyed. Businesses were asked to self-report the extent of damage to building elements, machinery and equipment, and contents and inventory. Note that building elements include both structural (shear walls, frames, etc.) and nonstructural components (façades, windows, ceilings, partition walls, plumbing, heating, ventilation and air-conditioning (HVAC) equipment, etc.). While few businesses (less than 25% in our convenience sample of businesses) experienced moderate or extensive damage to building elements or machinery and equipment, a larger percentage (almost 50% in our convenience sample) reported moderate or extensive damage to contents and inventory. Nearly 75% of businesses in our convenience sample reported utility outages (typically power or water), but they were brief and did not impact their ability to resume operations.

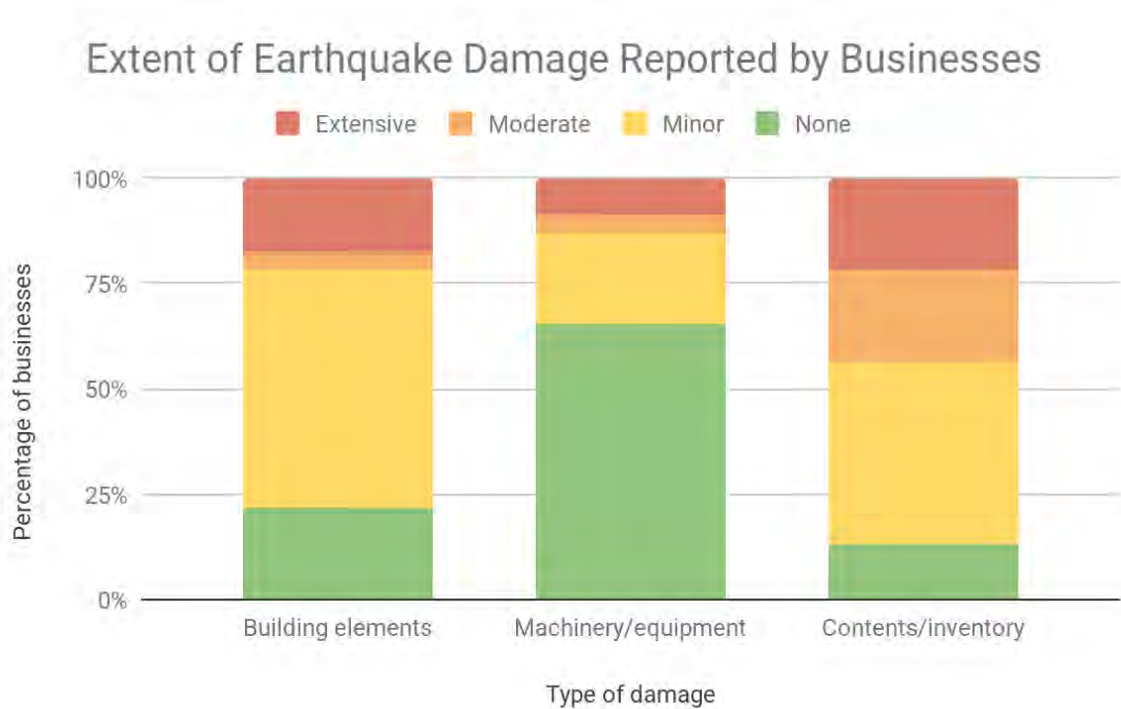


Figure 3. Extent of earthquake damage reported by businesses surveyed. Note that building elements include both structural (shear walls, frames, etc.) and nonstructural components (façades, windows, ceilings, partition walls, plumbing, HVAC equipment, etc.). Because of the small sample size and nonrandom sampling, data are not representative of businesses in the Anchorage region.

Figure 4 shows the duration of downtime reported by the 23 businesses surveyed. The vast majority (over 80% in our convenience sample) reopened within a week of the earthquake, with over half (60% in our convenience sample) reopening within a day. The two businesses that were still closed at the time of the survey, which was over 3 months after the earthquake, indicated that they planned to reopen. Figure 5 shows the duration of downtime as a function of the severity of damage reported to building elements, equipment and machinery, and contents and inventory. As expected, damage is correlated with downtime, although a few outliers can be observed (e.g., extensive building-element damage resulting in less than 1 day of downtime). Additional study is required to understand if these outliers are the result of reporting errors or if the businesses leveraged adaptive capacity to speed recovery in spite of significant damage.

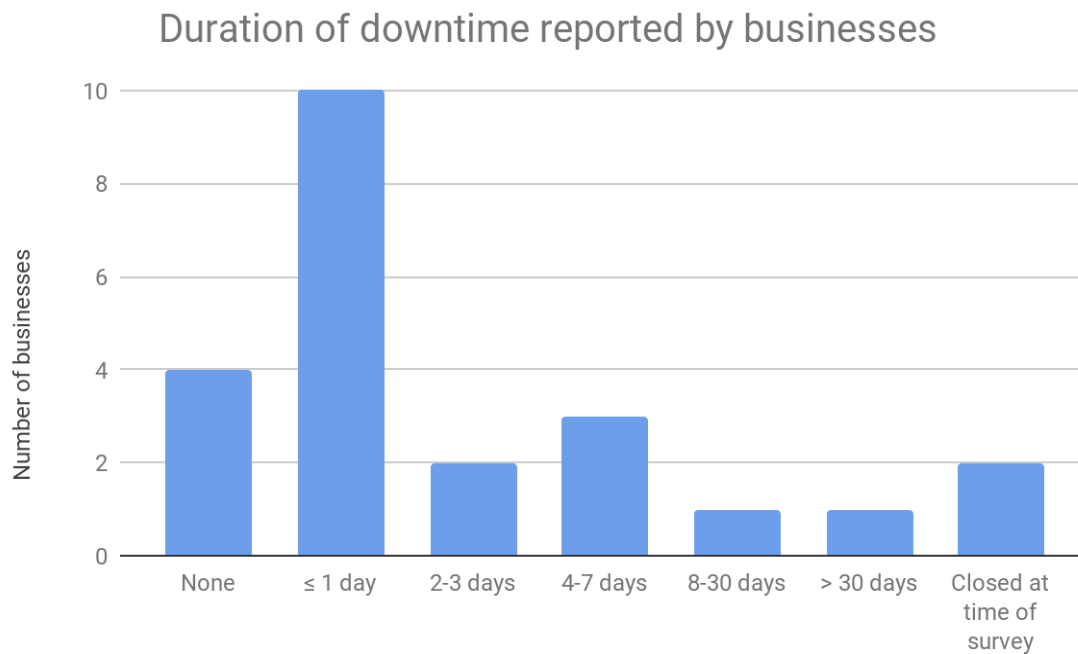
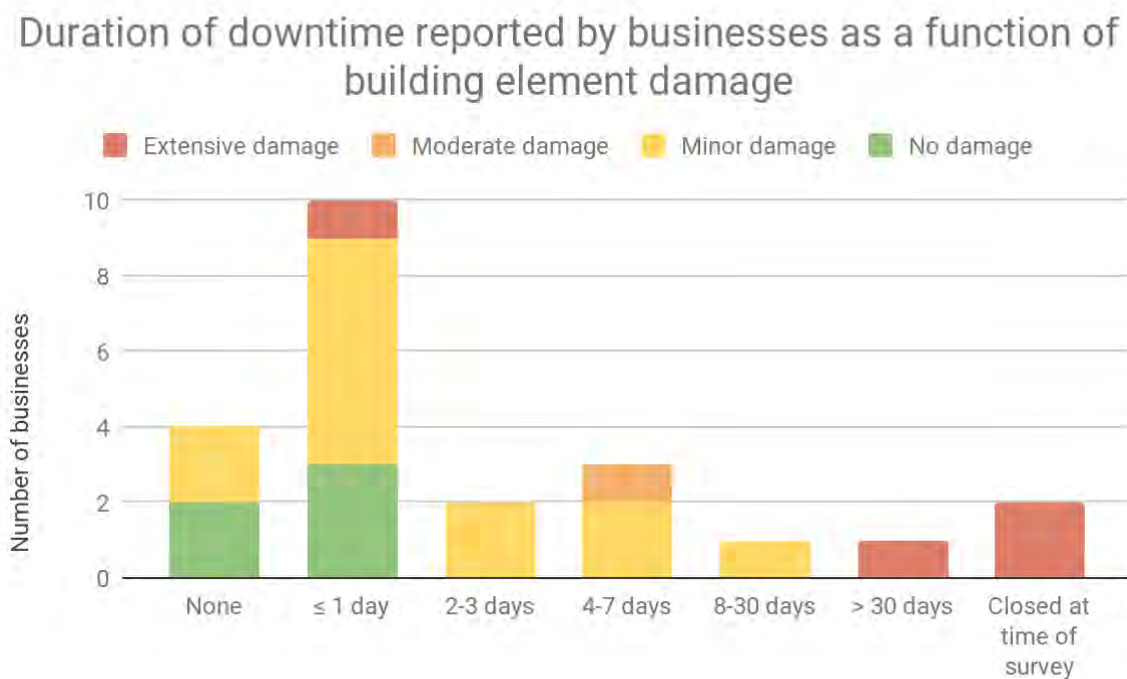
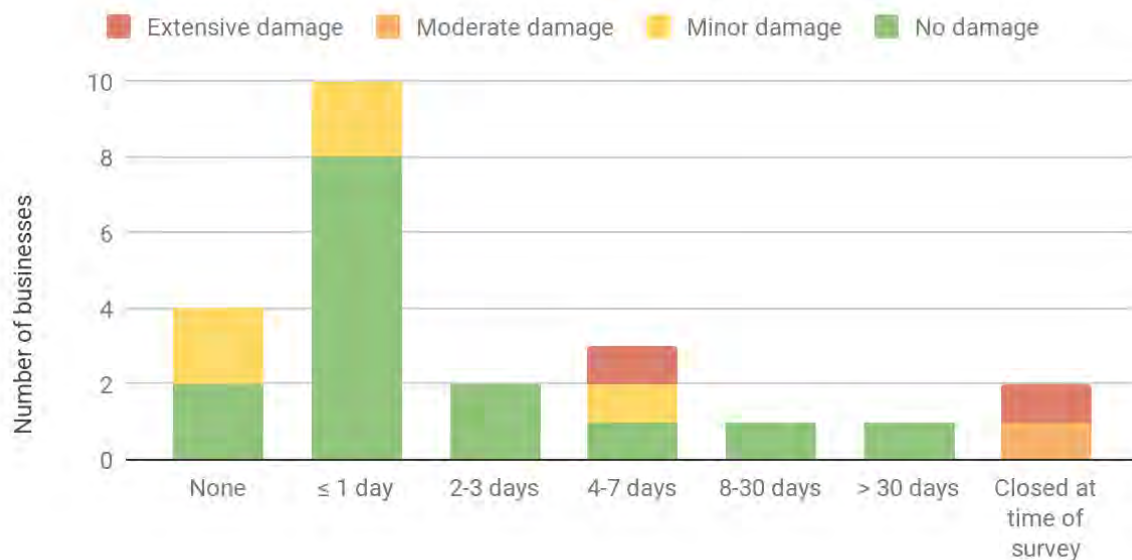


Figure 4. *Duration of downtime reported by businesses surveyed. Because of the small sample size and nonrandom sampling, data are not representative of businesses in the Anchorage region.*



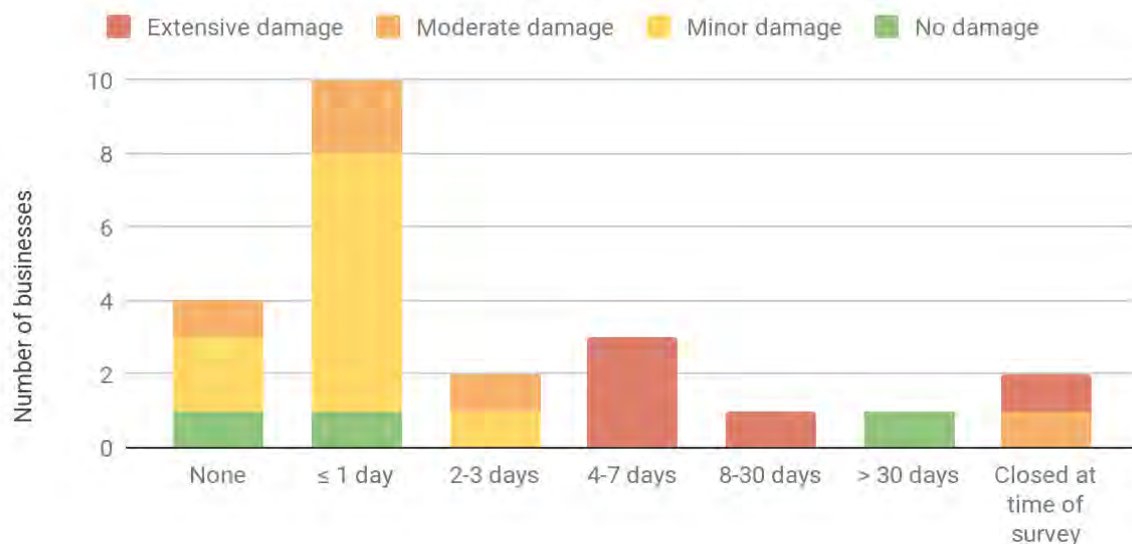
(a)

Duration of downtime reported by businesses as a function of equipment damage



(b)

Duration of downtime reported by businesses as a function of inventory damage



(c)

Figure 5. Duration of downtime as a function of damage to (a) building elements, (b) machinery and equipment, and (c) contents and inventory. Note that building elements include both structural (shear walls, frames, etc.) and nonstructural components (façades, windows, ceilings, partition walls, plumbing, HVAC equipment, etc.). Because of the small sample size and nonrandom sampling, data are not representative of businesses in the Anchorage region.

Figure 6 reports the recovery status of the businesses at the time of the survey. Businesses were asked to self-report where they felt they were in the recovery process and were provided a standard set of choices, as shown in the figure. Given the limited damage and downtime experienced by the businesses surveyed, all but two reported that they had

mostly or fully recovered. Because the survey focused on businesses with damage, and most of them performed well, we can infer that, overall, businesses in Anchorage were quite resilient to the impacts of the earthquake.

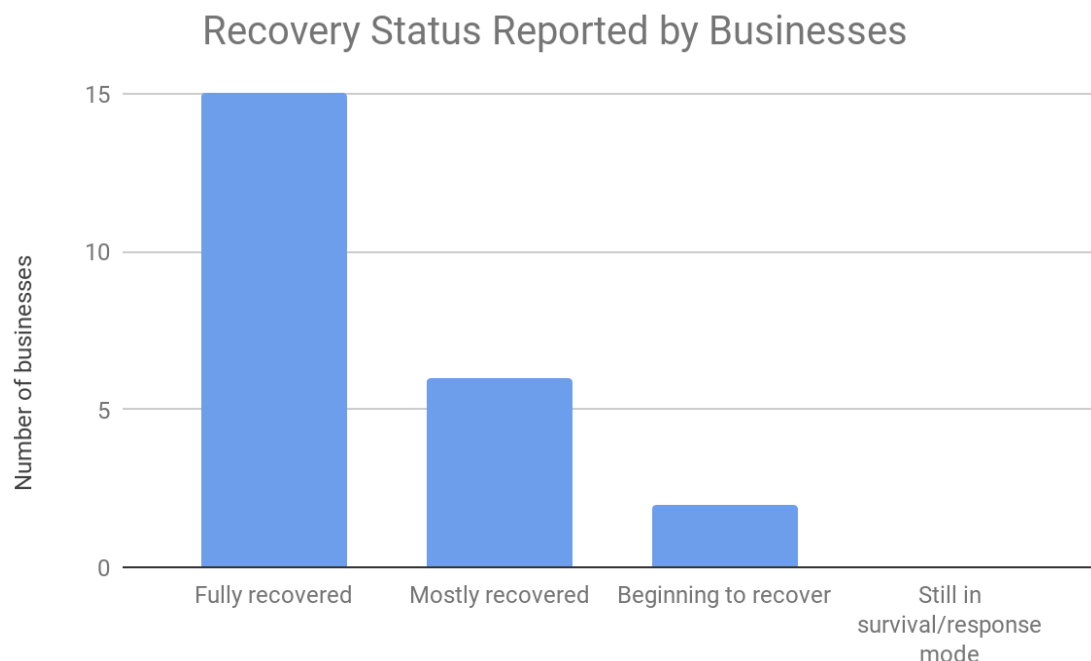


Figure 6. Recovery status of businesses surveyed. Because of the small sample size and nonrandom sampling, data are not representative of businesses in the Anchorage region.

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