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THE ANCHORAGE, ALASKA M7.1 EARTHQUAKE OF NOVEMBER 30, 2018: FINDINGS FROM A POST-EARTHQUAKE INVESTIGATION ON SELECTED POWER AND INDUSTRIAL FACILITIES

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ABSTRACT

The Electric Power Research Institute (EPRI) Seismic Qualification Utility Group (SQUG) instituted a post-earthquake investigation program in 1985 to facilitate the collection of experience data relevant to the nuclear power industry. The goal of the program is to advance the use of earthquake experience data as a cost-effective method for seismic qualification and fragility evaluation of nuclear power plant (NPP) equipment. EPRI continues to update the database by collecting experience data from new earthquakes to expand the volume and diversity of the data and confirm the established equipment class caveats and definitions in light of contemporary seismic events. Reviews of new earthquakes are prioritized based on the epicentral ground motion accelerations, the presence of industrial sites with equipment similar to typical nuclear installations, the likelihood of accessing these sites to document the equipment performance, the equipment diversity and vintage, and known instances of abnormal performance that could augment the existing experience. On November 30, 2018, Anchorage, Alaska, and surrounding areas were shaken by a M7.1 earthquake centered 16 km north of downtown. EPRI visited a total of sixteen sites located in the epicentral region following the earthquake, including three substations, seven power generating plants, and three water/wastewater treatment plants. This earthquake was of particular interest to EPRI because a significant number of facilities were subjected to relatively large ground motions. The site operators were also interested in working with EPRI on the investigation of their facilities, providing important insights on the equipment and system configuration and performance. Moreover, several power facilities were constructed within the last ten years, which afforded an opportunity to evaluate the applicability of SQUG guidance to newer vintage equipment. EPRI 3002018221 (2020a) documents the details of this EPRI investigation. This paper summarizes the main findings of that report and focuses on the most important lessons learned for the nuclear power industry.

BACKGROUND

SQUG began the post-earthquake investigation program in 1985 to collect and organize earthquake performance data relevant to the electric power industry, with an emphasis on data applicable to NPPs. The goal of the program is to advance the use of earthquake experience data as a cost-effective method for seismic qualification and fragility evaluation of NPP equipment. As such, SQUG investigations have focused on electrical and mechanical equipment representative of NPP safety systems. The experience data have been organized into a database, originated and maintained by EPRI/SQUG. The latest version of the database at the time of this post-earthquake investigation was eSQUG v2.7[1] (EPRI (2017a)). The v2.7 database contains information from thirty-two worldwide earthquakes spanning 1971-2010 and includes about 3,000 equipment datasets[2] segregated into twenty-eight equipment classes. Twenty of those classes were initially established based on a review of an earlier version of the database in response to the U.S. Nuclear Regulatory Commission (USNRC) Unresolved Safety Issue (USI) letter A-46 (USNRC, 1987). Each of these twenty classes is associated with a set of equipment-class-specific criteria or "caveats" used to determine if an equipment item is similar to equipment that performed well in actual earthquakes (e.g., adequate anchorage, free of interaction with surrounding equipment, class-specific weight and dimension limits). If these caveats are met, there is high confidence that the equipment seismic capacity exceeds the ground motion levels experienced at the SQUG database sites. The database has been used for a variety of applications, including to demonstrate equipment seismic adequacy in response to USI A-46 (e.g., GIP 3-A (SQUG, 2001)), to estimate probabilistic seismic capacities for NPP equipment (e.g., EPRI 3002012994 (2018), EPRI 3002011627 (2017b)), and to review the likelihood of losing offsite power after an earthquake (e.g., EPRI 3002015993 (2019)). EPRI continues to update the database by collecting experience data from new earthquakes, with the objective of expanding the volume and diversity of the data and confirming the established class caveats and definitions in light of contemporary seismic events.

EARTHQUAKE OVERVIEW

A magnitude 7.1 earthquake occurred 16 km north of downtown Anchorage, Alaska, on Friday, 30 November 2018, at 8:29 a.m. local time. The focal depth of the earthquake was 47 km below the surface. According to the U.S. Geological Survey (USGS) earthquake summary (USGS, 2020), shaking reached a Modified Mercalli Intensity (MMI) of VII and peak ground accelerations (PGAs) exceeding 0.1g were recorded throughout a 100 km radius from the epicenter. Six minutes later, a magnitude 5.7 aftershock occurred 4 km northwest of downtown Anchorage. Four more aftershocks greater than magnitude 5.0 were recorded within the following 48 hours. No deaths were documented as a result of the mainshock, but significant property damage was reported and estimated to be at least $76 million (Alaska Earthquake Center, 2019). Reported damage includes cracked and collapsed roads, fallen chimneys, broken ceilings and partitions, sheared small dimeter gas and water lines due to ground failures, and sliding of poorly anchored and unanchored equipment (StEER, 2018). Power outages occurred over portions of downtown, but according to the local utilities, there was not complete grid failure. Most of the damage to the electric power network resulted from typical failure modes such as insulator shorting, transmission lines making contact, or sensor tripping at substations.

STRONG GROUND MOTIONS

The dense local array of strong motion instruments around Anchorage allows the earthquake ground motion to be reasonably estimated at facilities over an extended region affected by the earthquake. The USGS ShakeMap for the M7.1 mainshock (03-08-2019 version) estimates PGAs exceeding 0.28g throughout downtown (USGS, 2020). The USGS ShakeMap was generated using data from 138 recording stations located within 430 km of the epicenter plus 212 Did-You-Feel-It (DYFI) reports. Digitized records (e.g., acceleration time histories and response spectra, displacement data) from ninety-one stations are publicly available on the Center for Engineering Strong Motion Data (CESMD) online repository

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[1] A newer version (eSQUG v3.0, EPRI (2021)) was recently published and incorporates the data collected from this post-earthquake investigation.

[2] An eSQUG "equipment dataset" is a is a collection of information describing a component including dimensions, location, photos, etc., and a summary of its performance during and after the earthquake. The word "record" is used interchangeably on eSQUG and in this paper for "dataset."

(CESMD, 2020). More than thirty of those ninety-one stations are located near downtown Anchorage (Figure 1). Recorded PGAs in Anchorage typically ranged from 0.20g to 0.45g. A full list of available recording stations, epicentral distances, and maximum recorded horizontal PGAs is included in EPRI 3002018221 (EPRI, 2020a).

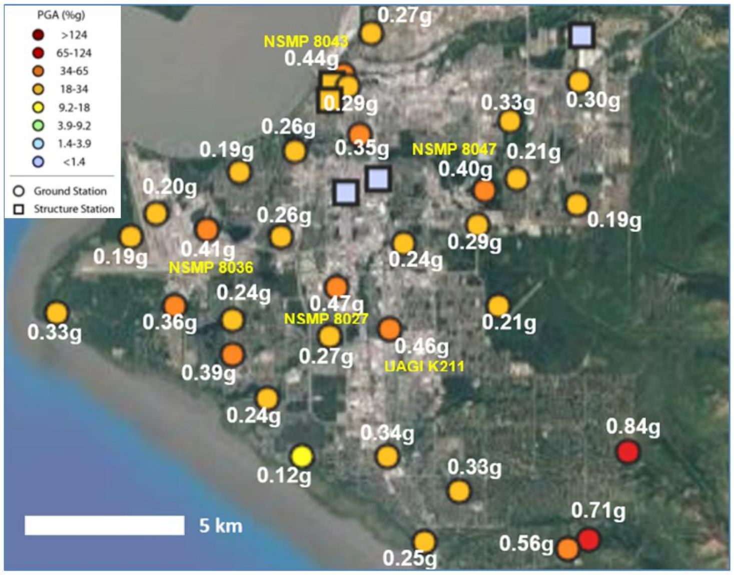

Figure 1. CESMD Recording Stations near Downtown Anchorage and Recorded PGA.

The five recording stations in Anchorage with the highest PGAs are identified in yellow text in Figure 1. The maximum peak spectral acceleration among these five stations is 2.1g, which was recorded at NSMP Station 8043 near downtown (reproduced below in Figure 2). The vertical response is generally weaker than horizontal and shifted toward higher frequencies. Most of the horizontal spectra peak at or below 5 Hz. The response spectra characteristics and the heterogeneous PGA map in Figure 1 indicate that the earthquake produced variable motions across Anchorage. Except for a few locations, the 2018 mainshock generally produced horizontal broad-banded demands comparable to the SQUG Reference Spectrum 1.2g broad-banded spectral response (SQUG (2001)).

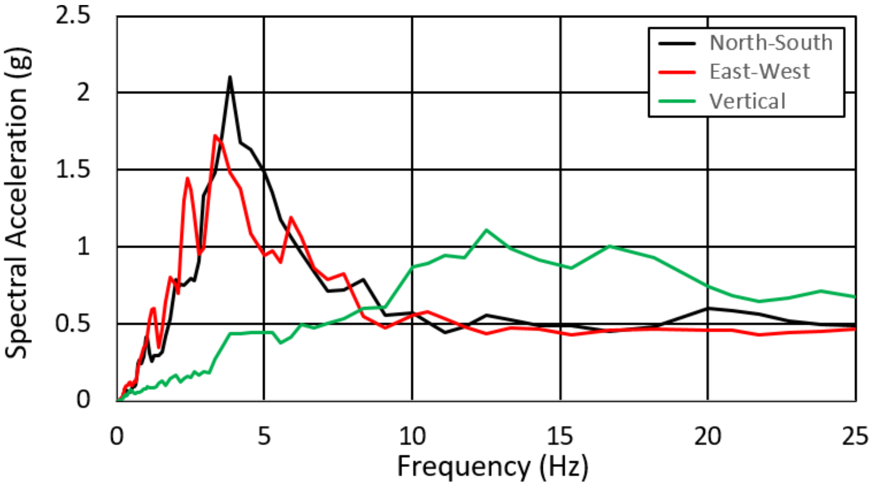

Figure 2. Ground Response Spectra at NSMP Station 8043.

SITES INVESTIGATED

The post-earthquake data collection efforts focused on key power and industrial facilities located in the epicentral area. The criteria for selecting the sites included:

- Location in the vicinity of the strongest ground motion estimates
- Likelihood of containing substantial inventories of equipment similar to NPP installations
- Likelihood of accessing the site and collecting data
- Evidence of damage or abnormal equipment performance

The reconnaissance team selected sixteen sites to visit over the course of six business days at the beginning of September 2019 (Figure 3). The sites included power generating stations and substations operated by three electric power utilities (Chugach Electric Association (CEA), Municipal Light & Power (ML&P), and Matanuska Electric Association (MEA)), water and wastewater treatment plants operated by the Anchorage Water and Wastewater Utility (AWWU), and other infrastructures such as the Port of Alaska (POA), the Alaska Native Medical Center (ANMC), and a fire station (Rabbit Creek). For several sites, an on-site or nearby record was available on the CESMD repository. As such, the local motion could be reasonably estimated with little uncertainty. For other locations without a nearby record, the local PGA was estimated using a USGS PGA contour map (USGS, 2020). The site PGA estimates[3] at these sixteen sites ranged 0.19g to 0.50g, as discussed in the following sections.

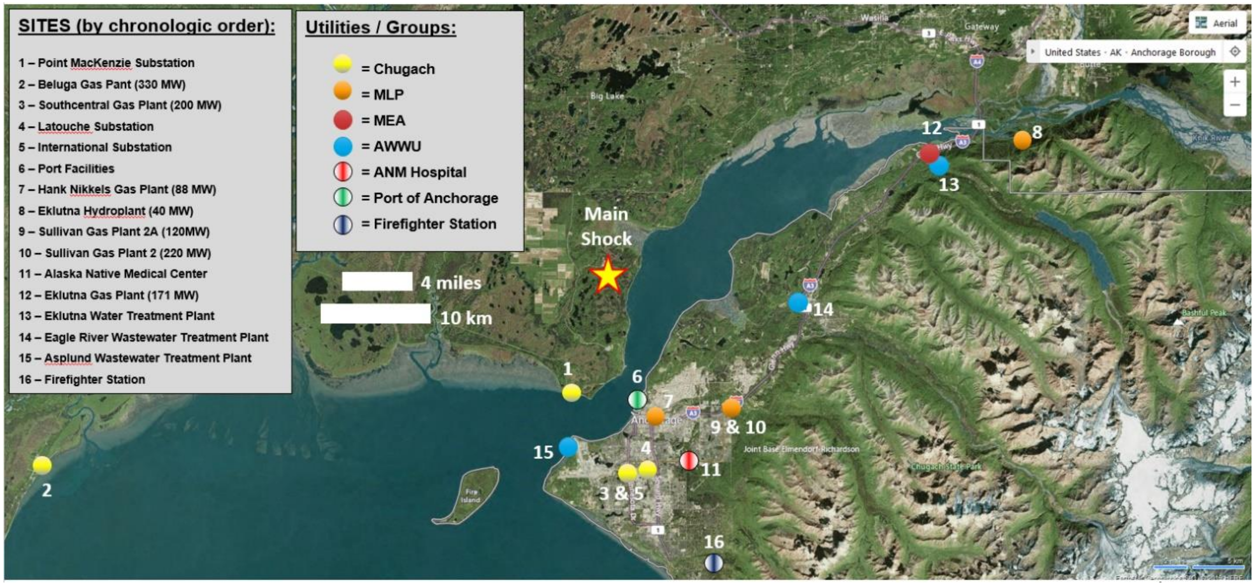

Figure 3. Location of Visited Sites (Background Image from Map Data ©2019 Google).

EXPERIENCE DATA COLLECTION PROCESS

Information on each facility, its performance during the earthquake, and any damage or adverse effects caused by the earthquake were collected through interviews with the facility management and operating personnel, reviews of utility internal reports on the earthquake effects and repair efforts, review of design drawings, walkdowns of the individual facilities, and inspection of the equipment and systems. The

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[3] EPRI 3002018233 (EPRI, 2020b) develops refined PGA and spectral acceleration estimates that more rigorously account for spatial distribution of available ground motion records.

facility operators were all very accommodating and willing to share their experience, which greatly aided the data collection process. Information on specific equipment performance was provided by the utilities ahead of the field investigation, which assisted in making the walkdowns effective and efficient. The information collected at each site was documented in the form of photos and videos of the equipment, rooms, and buildings visited, walkdown area sketches identifying the location of the equipment cataloged, and walkdown sheets documenting important equipment information subsequently used to develop the experience database (e.g., manufacturer, model, equipment configuration, seismic performance). The walkdown sheets used for this investigation were a succinct version of typical data collection forms used in nuclear walkdowns for seismic probabilistic risk assessment (SPRA). The information collected for each site and for each specific item of equipment was cross-checked and compiled into a single record in a spreadsheet. The resulting database includes 531 datasets from the sixteen sites visited. Table 1 lists the number of equipment items reviewed in each equipment class employed in the SQUG online database (eSQUG v2.7 (EPRI, 2017a)).

Table 1: Alaska Equipment Records Breakdown by eSQUG Equipment Class.

Equipment Class	No. of Records
Air Compressors	22
Air Handlers	17
Air Operated Valves	11
Battery Racks	24
Chillers	1
Control Panels	94
Cranes	23
Distribution Panels	39
Engine Generators	13
Fans	24
Horizontal Pumps	30
Horiz. Tanks & Heat Exchangers	6
HVAC Damper	2
HVAC Duct	2
Instrument Racks	15
Low Voltage Switchgear	15
Medium Voltage Switchgear	19
Miscellaneous	11
Motor Control Centers	48
Motor Generators	2
Motor Operated Valves	22
Piping and Tubing	2
Sensors	3
Static Inverters & Battery Chargers	31
Transformers	30
Vertical Pumps	17
Vertical Tanks on Legs or Skirts	8
Total	531

ELECTRIC POWER SYSTEM

Alaska's vast territory is divided into eleven energy regions. The Railbelt region includes Anchorage and is serviced by six electric utilities: Golden Valley Electric Association (GVEA), MEA, CEA, Homer Electric Association (HEA), Anchorage ML&P, and the City of Seward Electric System (SES). The power grid is an interconnected network, with multiple utilities sharing construction and operation costs of some of the power plants (e.g., Eklutna Hydro-plant, Southcentral Power Project). Figure 4 shows maps of the high-voltage transmission network around Anchorage. The state capital grid is surrounded by a circle of substations connected to two 115 kV lines from Palmer and the Kenai Peninsula and to 138 kV and 230 kV lines routed through the Point MacKenzie and Six Mile West substations. Each high-voltage transmission line can be independently powered by generating stations distributed along their path. The post-earthquake investigation focused on reviewing substations and power plants of three utilities: CEA, ML&P, and MEA. Table 2 summarizes the substations and power plants reviewed. Nearly all the power plants primarily rely on the abundant gas reserves in the area for their fuel. Most of the generating units built before 1985 are still operating at peak loads. Three large power plants were built in the last seven years. All the substations and power plants reviewed are located within 60 km of the epicenter and experienced a PGAs from 0.20g to 0.47g. As a result of the M7.1 mainshock, six out of fourteen operating units tripped offline (Table 2, footnote "a"). Power outages occurred over portions of downtown. Most of the damage to the electric power network resulted from typical failure modes such as insulator shorting, transmission lines making contact, or sensors tripping at substations. One plant tripped when the digital control system (DCS) input/output (I/O) cards in an electrical cabinet dislodged because they were missing their retaining screws. These failures were quickly corrected, and power was restored to nearly all customers within 12 hours. Most of the equipment damage and malfunctions were observed at the Beluga Power Plant units (Table 2), which are the oldest gas-powered units in operation and were built before 1980. EPRI 3002018221 (EPRI, 2020a) provides detailed descriptions of the performance of each plant and substation visited, including notable instances of abnormal equipment performance.

Table 2: Information on the Electric Power Facilities Visited.

Site Name	**Utility**	**Plant Type**	**Units No.**	**Start Date of Operations**	**Post-earthquake Operation**	**Estimated PGA (g)**	**km from Epic.**
Point MacKenzie Substation	CEA	230 kV/138 kV Substation	-	-	-	0.32	11
Beluga Power Plant		6x1 Combined Cycle	7	1968 (Unit 1-2) 1973 (Unit 3) 1975 (Unit 5) 1976 (Unit 6) 1978 (Unit 7) 1981 (Unit 8)	(c) (c) (c) (c) (c) (d)	0.24	60
Southcentral Power Project		3x1 Combined Cycle	4	2013 (Unit 10-12) 2013 (Unit 13)	(b) (a)	0.22	20
Latouche Substation		35 kV Substation	-	-	-	0.24-0.47	20
International Substation		138 kV Substation	-	-	-	0.22	20
Hank Nikkels Plant 1	ML&P	4 Gas Powered Turbines	4	1962 (Unit 1) 1964 (Unit 2) 2007 (Unit 3) 1972 (Unit 4)	(d) (d) (c) (a)	0.29	15
Eklutna Hydro-Project		2 Hydro-turbines	2	1955 (Unit 1-2)	(a)	0.20-0.24	45
George Sullivan Gas Plant 2A		2x1 Combined Cycle	3	2016 (Unit 9) 2016 (Unit 10-11)	(b) (a)	0.30	18
George Sullivan Gas Plant 2		2x1 Combined Cycle + Standalone Simple Cycle	4	1975 (Unit 5) 1979 (Unit 6) 1979 (Unit 7) 1984 (Unit 8)	(d) (d) (c) (c)	0.30	18
Eklutna Generation Station	MEA	10 Engines w/ Dual Fuel Option	10	2015 (Units 1-2) 2015 (Unit 3-6) 2015 (Unit 7-8) 2015 (Unit 9-10)	(b) (c) (b) (c)	0.28	35

(a) Unit was operating during the earthquake and tripped
(b) Unit was operating during the earthquake and did not trip
(c) Unit was not in operation during the earthquake but has been powered at least once after December 1, 2019
(d) Unit had been decommissioned before the earthquake

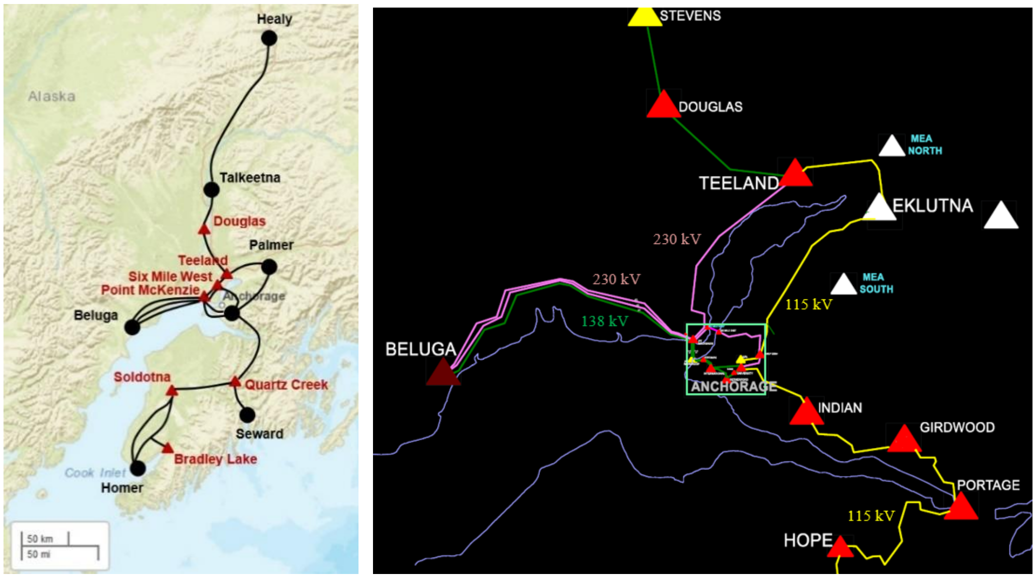

Figure 4. High Voltage Transmission Network Around Anchorage (Courtesy of CEA).

WATER AND WASTEWATER SYSTEMS

AWWU is the largest water and wastewater utility in Alaska. Its service area is 324 square kilometers. The AWWU network includes five water/wastewater treatment plants, 2,575 kilometers of underground pipeline, fourteen active wells, twenty-two water reservoirs, thirty-eight wastewater pump/lift stations, two septage receiving stations, thirty-four booster stations, and 7,200 fire hydrants. The overall seismic performance of this large system was exceptionally good. The system was not contaminated and remained pressurized, except for isolated areas affected by local soil failures and frigid temperatures. One of the major breaks downstream of the Girwood reservoir, which resulted in drainage of 950,000 liters of water stored for the Girwood community, was resolved by mid-afternoon. The EPRI investigation focused on AWWU's largest plants (Eklutna Water Treatment Plant (EWTP), Eagle River Wastewater Treatment Plant (ERWWTP), and Asplund Water Pollution Control Facility (AWPCF), Figure 3). Table 3 summarizes the sites reviewed. The plants were built before 1992. Their treatment capacity ranges 9.5

Table 3: Information on the Water and Wastewater Facilities Visited.

Site Name	Start Date of Operations	Post-earthquake Operation Performance	Estimated PGA (g)	km from Epic.
Eklutna Water Treatment Plant	Commenced in 1988	Experienced a 45 min. power outage but operations continued during and after the earthquake thanks to gravity-driven treatment systems.	0.28	36
Eagle River Wastewater Treatment Plant	Built in the 1970s. Capacity expanded in 1991	Operation resumed two hours after the earthquake, after a leak in a threaded elbow pipe was corrected. Operation resumed on emergency diesel generators until grid power was restored in the evening.	0.32	18
Asplund Water Pollution Control Facility	Built in 1972 and upgraded in the mid-1980s	Operable. No outage recorded and emergency generators were not activated.	0.19-0.20	12

million liters per day (MLD) to 220 MLD. The plants are located within 35 km of the epicenter and experienced a PGA from 0.19g to 0.32g. As a result of the M7.1 mainshock, two plants lost offsite power. One of the two plants (EWTP) was operable during and after the earthquake thanks to its gravity-driven treatment systems. ERWWTP resumed operation on emergency diesel generators two hours after earthquake after fixing a 1,500 liters per minute leak in a 5.1 cm diameter threaded galvanized elbow that had sheared off due to differential movements. AWPCF is connected to the grid through two independent transmission lines and operates primarily on gravity-fed systems. This configuration likely helped the site maintaining power following the mainshock, even though the closest substation (Postmark) suffered multiple transformer trips. No major equipment damage was observed at these three plants. Most of the damage resulted from cracks opening in structural elements, some of which might have even predated the earthquake. EPRI 3002018221 (2020a) describes the performance of each AWWU site visited in detail.

ADDITIONAL INFRASTRCTURE

The focus of this post-earthquake investigation was on power and water facilities. Three additional infrastructure systems were reviewed because of the possibility of collecting important experience data: POA, ANMC, and Rabbit Creek Fire Station (Figure 3). EPRI 3002018221 (2020a) documents the findings from these sites, which are briefly summarized in Table 4. These facilities were built between 1960s and 1990s, are located within 25 km of the epicenter, and experienced PGAs from 0.27g to 0.50g.

Table 4: Information on the Additional Infrastructure Facilities Visited.

Site Name	**Post-earthquake Operation Performance**	**Estimated PGA (g)**	**km from Epic.**
Port of Alaska	Limited damage to dock piles, exacerbated by existing corrosion. No significant impact on operations. Fuel handling operations resumed the same data and loading operations the following day after completing safety inspection.	0.27	8
Alaska Native Medical Center	Lost grid power for two hours. Standby generators fired automatically in 10 seconds to restore site power. Some equipment sprayed by a water leak but operable after being dried. No significant impact on operations.	0.29-0.41	14
Rabbit Creek Fire Station	Minor damage. Operations unaffected.	0.50	25

Damage at the Rabbit Creek Fire Station and the nearby Bear Valley elementary school was relatively minor and limited to non-structural components, despite the large PGA recorded on-site (0.50g). The POA suffered some damage to parts of the pile foundations supporting the dock, but loading/unloading activities were resumed the following day after the facilities were inspected and deemed safe for operation. Damage in the dock piles had been likely exacerbated by pre-existing section losses and seam weld degradations due to the extreme corrosion environment (the piles were originally 1.1 cm thick and have since lost up to 75% of their section). An inspection of the yard the same day of the mainshock identified some ground failures (e.g., lateral spreads and sand boils) that had no significant impact on the operations. The POA performance was excellent considering the proximity to the epicenter (8 km) and the degraded pile capacity. The ANMC hospital lost power from the grid for about two hours. The standby emergency generators fired automatically and restored station power. Water, wastewater, and natural gas systems were not interrupted. The only significant earthquake effects were leakages from 3.8 cm diameter pipes part of the auxiliary cooling water system. At one location on the third-floor level inside a vertical shaft spanning multiple floors, the small diameter branch line was located too close to a platform beam and sheared off when the main line racked. The broken pipe spayed some of the mechanical equipment near the chillers in the basement. The equipment was dried and returned to service. Another earthquake-related anomaly was a motherboard failure that rendered an elevator inoperable. These earthquake effects had no significant impact on the hospital operations.

SUMMARY AND CONCLUSIONS

On the morning of Friday, 30 November 2018, Anchorage was shaken by a M7.1 earthquake centered 16 km north of downtown. EPRI visited a total of sixteen sites located in the epicentral region, including three substations, seven power generating plants, and three water/wastewater treatment plants (Figure 3). The purpose of the investigation was to document the earthquake effects on equipment similar to NPP installation and to determine if any earthquake damage or failures would impact the SQUG methods and criteria developed based on earthquake experience data (e.g., GIP 3-A (SQUG, 2001)). The mainshock generated PGAs exceeding 0.1g throughout a 100 km radius and caused outages in multiple sections of the electric power grid. Most of the power losses resulted from failures at substations, such as pressure and level switches tripping transformers or brittle insulators and rigid busses breaking off. Fortunately, the earthquake struck early in the morning, and the utilities could immediately respond to the event by dispatching crews to the affected substations. Locked out relays were quickly tested and reset, and damaged equipment was promptly resolved or bypassed. Almost all the outages were resolved by Friday night. Six of fourteen power generating units tripped offline (Table 2). The water and wastewater treatment plants include numerous gravity-driven systems and continued operations on emergency generators after offsite power was lost. None of the plants suffered significant structural or equipment damage, and all the tripped power generating units were operable within a day.

The main conclusions from the M7.1 Anchorage 2018 post-earthquake investigation are:

- 531 equipment data samples were collected as part of this reconnaissance effort (Table 1) and have been entered into the EPRI earthquake experience database (eSQUG v3.0, EPRI (2021)). The diverse data samples spanned twenty-seven equipment classes from sixteen different sites and had a large sample of newer vintage equipment due to the relatively new facilities reviewed (Tables 2).
- All earthquake effects observed are attributable to failure modes previously documented in the SQUG database and excluded by existing SQUG caveats and equipment class definitions.
- The vast majority of the equipment items reviewed performed very. The typical peak horizontal average broad-banded spectral acceleration recorded in the epicentral region is comparable to the SQUG Reference Spectrum 1.2g broad-banded spectral response. The equipment performance data collected in this investigation provide further evidence that equipment typical of NPP can withstand the 1.2g Reference Spectrum level with high confidence.

Secondary conclusions and ancillary insights from this investigation are:

- The Anchorage infrastructure generally performed very well during and following the M7.1 earthquake as well as the aftershocks. The power, water, and port/airport facilities were able to return to normal operations relatively quickly. Some hospitals and schools suffered minor damage to non-structural systems (e.g., ceiling, fire sprinklers) and to large mechanical and electric equipment (e.g., boilers, transformers, fans) due to inadequate bracing or insufficient anchorage. Most of these instances of poor anchorage performance affected equipment built in the 1980s, confirming that older commercial design provisions for equipment anchorage were less effective at preventing earthquake damage than contemporary criteria.
- The grid elements (i.e., generation, transmission, distribution systems) performed well with few exceptions, such as the 230 kV line at Point Mackenzie substation. Roughly half the population lost power, but almost all the outages were resolved within a day.

- One earthquake effect not documented before that may be relevant to nuclear operations is the digital button inoperability at the Hank Nikkels Plant 1. Unit 3 was not in operation during the earthquake, and Unit 4 was starting up. The operator in the control room shut down Unit 4 immediately using the digital control logic on the computer monitor. The operator attempted to click the mouse on the on-screen shut-off button at least ten times without success during the earthquake due to difficulty in controlling the mouse during the strong shaking. A physical button to manually activate the shutdown process would have been better in that situation. The plant has subsequently installed a physical emergency stop button in the control room. This malfunction underscores a potential limitation of digital control systems: human-computer interfaces requiring motor control like a computer mouse used to press an on-screen button may be unreliable during an earthquake.
- Gravity-driven systems helped water and wastewater treatment plants continue operations despite losing power. This demonstrates gravity forces could be effectively used to increase system seismic robustness by removing the system dependency to external power sources. This observation may be relevant for newer generations of NPPs which more heavily rely on gravity-driven safety systems.
- The power and water facilities in the epicentral region were designed to incorporate increased margins. For example, the local utilities are aware of the difficulties of transporting large components to their remote sites, some of which are accessed only by plane or helicopter. Therefore, critical structures and equipment supports were often designed with extra margin to compensate for the fact that retrofit operations are expected to be difficult and lengthy, particularly in the winter season. Those extra design margins likely contributed to the good seismic performance and rapid recovery despite the severe ground shaking.

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