Final Technical Report

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National Liquefaction Loss Model for PAGER

Laurie G. Baise, Professor and Chair and Alexander Chansky, M.S. student

Department of Civil and Environmental Engineering, Tufts University, 200 College Ave, Medford, MA 02155, 617-627-2211; 617-627-3994 (fax), Laurie.baise@tufts.edu

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Abstract

Liquefaction is a secondary hazard that occurs during earthquakes and can cause severe damage to overlying infrastructure. As a result, liquefaction can be a significant contributor to loss due to earthquakes as observed during the 2011 New Zealand earthquakes or the 1995 Kobe earthquake. A geospatial liquefaction model developed by Zhu et al. 2017 and implemented by the USGS on the earthquake overview page within the ground failure tab can be used to estimate liquefaction extent after an earthquake. The geospatial liquefaction model estimates liquefaction spatial extent (LSE) using globally available parameters: water table depth (Fan et al 2013), annual mean precipitation (Hijmans et al., 2005), distance to waterbody, slope-based V_{s30} (Wald and Allen 2007), peak ground velocity (ShakeMap, Worden and Wald, 2016), and peak ground acceleration (ShakeMap).

The total areal extent over which soil is expected to liquefy in an earthquake is calculated for each event (TLSE) and evaluated against observed liquefaction (Rashidian and Baise, 2020). The USGS Pager system utilizes a slightly different algorithm to calculate a variation of TLSE referred to as “aggregate liquefaction hazard” or “Estimated area exposed to (liquefaction) hazard”, which is abbreviated as Htot. The USGS Pager system also calculates “aggregate liquefaction population exposure.” However, neither the geospatial liquefaction model nor the USGS Pager system currently predict infrastructure or economic loss due to liquefaction.

We present a liquefaction loss database based on numerous past events with a focus on events in the United States. This database is used to relate economic loss due to liquefaction in historical events to the estimated area exposed to liquefaction hazard. The database also assigns infrastructure damages to one of three categories and one of several subcategories. This allows for more detailed loss analysis by comparing amount of an infrastructure category’s loss with an infrastructure category’s estimated hazard exposure. Relationships developed in this project could be utilized by the USGS Pager System to estimate

economic loss due to liquefaction in future events. Future work will provide additional uncertainty analysis to provide more robust estimates of loss.

Additionally, we present fragility functions constructed on liquefaction damage states assigned relative to overall earthquake damage building on the work by Bird and Bommer (2004). While the fragility functions presented herein do not estimate liquefaction costs in future events, they provide probabilities of liquefaction causing minor/moderate damage relative to the overall event or major damage relative to the overall event based on an excitation measure, which in this case is Htot. Next steps in this research will be to develop fragility curves based on cost-based damaged states. This work can also be expanded by broadening the loss database to include earthquakes from around the globe.

1. Introduction

One of the most complete, systemic records of liquefaction damage can be found in Bird and Bommer (2004) where liquefaction damage is summarized across 50 global earthquake events. Bird and Bommer (2004) assigns one of three damage states to each of three infrastructure categories; buildings, utilities, and transportation. Their method of quantifying damage utilizes a general comparison of liquefaction damage in each infrastructure category with total earthquake damage for the event. This is done for the purpose of gauging how impactful liquefaction was for each category in comparison with total event damages. A key benefit of this system is its ability to quickly analyze many events for liquefaction impact.

However, a predictive analysis conducted using the Bird and Bommer (2004) methodology struggles to estimate infrastructure impact at a detailed level. There are no clear dollar values associated with upper or lower limits of each damage state. It is thus possible to have events of the same liquefaction damage state for the same category have remarkably different costs associated with their liquefaction damage. For example, using the Bird and Bommer (2004) schema, at least one collapsed bridge due to liquefaction defines the transportation category as having major damage due to liquefaction, its maximum damage state. Thus, an event which produces 20 collapsed bridges will be assessed similarly and placed into the same transportation damage state as an event with only one collapsed bridge. This causes issues in the analysis when assessing probabilities of exceeding damage state thresholds given an intensity measure, such as aggregate liquefaction hazard.

In this project, we build a detailed liquefaction loss database for the United States. This project develops the database of liquefaction damage and loss for 12 US events with reported liquefaction damage and 22 events without liquefaction damage reports. Five of the events without liquefaction damage have detailed reconnaissance reports while the remaining events were smaller and less well studied. By combining this dataset with that provided by Bird and Bommer (2004), we are able to establish liquefaction damage states and develop corresponding fragility functions. In addition, we explore methods to provide more detailed cost-based estimates of damage and loss using aggregate liquefaction intensity measures.

2. Geospatial prediction of liquefaction spatial extent

This project is designed to build on the geospatial liquefaction models by Zhu et al. (2015, 2017) and Rashidian and Baise (2020). These models have been adapted by the USGS and implemented as part of the Ground Failure tab of the earthquake overview. In order to make event-based predictions of liquefaction extent and subsequently loss, we need aggregate event-based estimates. Rashidian and Baise (2020) use TLSE for total liquefaction severity extent. In parallel, the USGS developed the estimated area exposed to liquefaction, Htot. Figure 1 displays values of LSE for each cell in percent, which represents the spatial extent of expected liquefaction. The total aggregate liquefaction hazard (TLSE or Htot), which is the estimated area exposed to liquefaction, is the sum of the area of each cell multiplied by the LSE percent for each cell.

For consistency with the USGS, we will use Htot for the aggregate extent calculation. The calculation for Htot, is represented by equation 1, where "$P_{i,j}$ is the ground failure probability at grid cell i,j $A_{i,j}$ is the area of cell i, j, m is the number of rows, n is the number of columns, $gm_{i,j}$ is the ground motion parameter at grid cell i, j, gm_{thresh} is the ground motion threshold, and P_{thresh} is the probability threshold" (USGS: Ground Failure Scientific Background).

$$\mathrm{H}_{tot} = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{P}_{i,j}\mathrm{A}_{i,j} \text{ for } gm_{i,j} \geq gm_{thresh} \text{ and } \mathrm{P}_{i,j} \geq \mathrm{P}_{thresh} \tag{1}$$

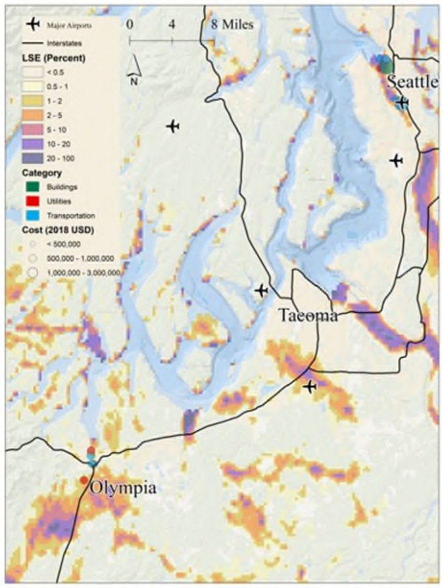


Figure 1: LSE values for 2001 Nisqually event projected into NAD 1983 (2011) StatePlane Washington North FIPS 4601 (Meters). Htot values were calculated from this by the summation of each cell's area multiplied with its LSE value.

The USGS also uses an aggregate statistic for estimated population exposure to liquefaction, pop_{exp}. The USGS uses LandScan 2016 for population density. The LandScan 2016 data, shown in Figure 2, shows ambient population (average over 24 hours) distribution using approximately 1 km (30" by 30") resolution. LandScan datasets incorporate cultural settlement practices and local population distribution models as no other distribution models accurately consider spatial data availability, quality, and scale.

Figure 2 displays how population exposure values are calculated for the 2001 Nisqually event. Figure 2a shows LSE from figure 1 mapped in the geographic coordinate system, WGS 1984, and resampled to the lower resolution of LandScan 2016. The rightmost panel of Figure 2, Figure 2c, represents the product of multiplying each cell from the LSE map with the population density, excluding cells where LSE cell has a value of less than 5%. The calculation can be shown in equation 2, where "$L_{i,j}$ is the population of grid cell i, j, m is the number of rows, n is the number of columns, $P_{i,j}$ is the ground failure probability at cell i,j, $gm_{i,j}$ is the ground motion parameter at grid cell i, j, gm_{thresh} is the ground motion threshold, and P_{thresh} is the probability threshold" (USGS, Ground Failure Scientific Background).

$$\mathrm{pop}_{exp} = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{L}_{i,j}\mathrm{P}_{i,j} \text{ for } gm_{i,j} \geq gm_{thresh} \text{ and } \mathrm{P}_{i,j} \geq \mathrm{P}_{thresh} \tag{2}$$

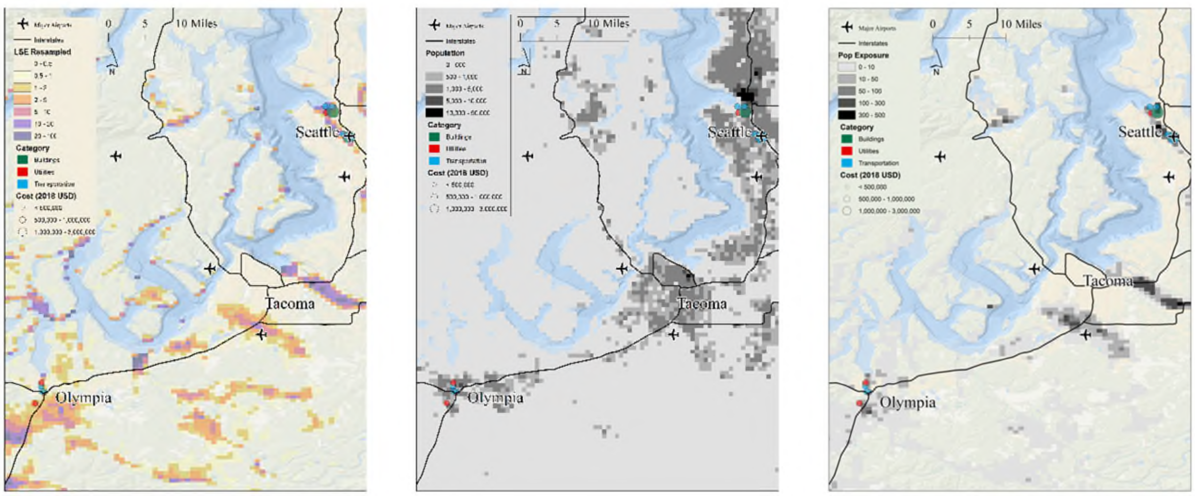


Figure 2. a: LSE Values for 2001 Nisqually event resampled to lower resolution matching LandScan 2016. **b:** Population density in Nisqually event's region obtained from LandScan 2016. **c:** Population exposure raster, calculated as the product of LSE and Population rasters.

3. Liquefaction Loss Database

The liquefaction loss database relied on sources in literature to identify liquefaction damage and then to classify the damage and quantify the loss. For each event, we relied on multiple sources as needed to identify and classify liquefaction damage. GEER reconnaissance reports were particularly useful for this purpose and were used as a primary source whenever available. GEER reconnaissance reports are each conducted by multiple geologists, seismologists, and geotechnical engineers. Another excellent resource for public reconnaissance reports is the Earthquake Engineering Research Institute (EERI). By analyzing other scientific articles or informal news articles in addition to the engineering reconnaissance reports, a more detailed and accurate catalog of liquefaction damages was made for each event. Table 1 provides the earthquake event information and reconnaissance report information used in this project.

Table 1: Primary sources used for each event in our database.

Event ID	Date	Mw	Name of Event	Htot	Sources
1	08/17/2015	4	Piedmont	0	Benedetti et al. (2015), Consulate (2015), Taylor (2015)
2	07/28/2008	5.4	Chino Hills	0.068	Kashighandi et al. (2008)
3	09/03/2000	5	Yountville	0.25	Eidinger et al. (2000)
4	12/22/2003	6.5	San Simeon	3.1	AirNav (2019), Archer et al. (2004), Holzer et al. (2004)
5	09/03/2016	5.8	Pawnee	7.1	Clayton et al. (2016)
6	08/23/2011	5.8	Mineral	11	Martin et al. (2011)
7	08/24/2014	6	Napa	26	Bray et al. (2014)
8	01/17/1994	6.7	Northridge	34	Abercrombie (2013), Stewart et al. (1994)
9	07/06/2019	7.1	Ridgecrest 7.1	35	Stewart et al. (2019)
10	10/16/1999	7.1	Hector Mine	49	Hough et al. (2000) Southern California Earthquake Data Center (1999)
11	02/28/2001	6.8	Nisqually	92	Bray et al. (2001)
12	04/29/1965	6.7	Puget Sound	120	Chleborad and Schuster (1990), Mineral Information Service (1965), Steinbrugge and Cloud (1965)
13	10/17/1989	6.9	Loma Prieta	160	Holzer (1990), McDonnell (1993), Museum of the City of San Francisco (1989), Seed et al. (1990), Taylor et al. (1990)
14	11/03/2002	7.9	Denali	290	Aho et al. (2003), Kayen et al. (2003), McCarthy (2003)
15	11/30/2018	7	Anchorage	330	Archbold et al. (2018), Franke et al. (2019)
16	04/04/2010	7.2	Baja	580	Meneses Kleinfelder et al. (2010), Stewart et al. (2010)
17	03/28/1964	9.2	Alaska	2100	Brocher (2014), Eckel (1967), Kachadoorian (1968), Logan (1967), McCulloch (1970), Grantz (1964)

To identify all liquefaction damage occurrences and to assess costs more accurately, all available resources were used. For example, for the 1964 Alaska event, there was no GEER report available, as GEER was not established until much later. However, many other resources, both academic and non-academic, were found describing damages. Four professional papers produced by the USGS gave detailed descriptors about many infrastructure damages. Although other sources existed, the USGS professional papers provided an exhaustive list of liquefaction damage for the 1964 event.

Each occurrence of liquefaction in the reconnaissance reports was evaluated as a damage occurrence and a feature/row in the database. Prior to cost estimates, the damage occurrence was categorized by infrastructure type: buildings, transportation, utilities and damage state (table 2). This categorization is consistent with Bird and Bommer (2004). The cost estimates for each damage occurrence were developed from direct cost estimates available in the literature or using the HAZUS—MH 2.1 Technical

Manual. Road costs were handled with a different approach as discussed below. The HAZUS-MH 2.1 Technical manual developed by the Department of Homeland Security; Federal Emergency Management Agency describes the multi-hazard loss estimation methodology used to estimate replacement costs for many infrastructures as well as the probabilities that some infrastructure pieces themselves will exceed thresholds of different damage states.

Table 2: Summary table of 17 US events with detailed reconnaissance reports in order of increasing Htot.

						Bird and Bommer, 2004			Rashidian and Baise, 2020		Chansky and Baise, working		
Date	Mw	Name of Event	State	Htot	PopExp	Buildings	Transportation	Utilities	Reconnaissance	GGLM	2018 Est Liq Costs (thousands)	2018 NOAA Costs (thousands)	Percent of Total Costs (%)
08/17/2015	4	Piedmont	CA	0	0	-	-	-	1	1	$0	-	-
07/28/2008	5.4	Chino Hills	CA	0.068	170	-	-	-	1	1	$0	-	-
09/03/2000	5	Yountville	CA	0.25	89	-	-	-	1	1	$0	$73,000	0
12/22/2003	6.5	San Simeon	CA	3.1	560	X	X	X	1	1	$1,343	$409,000	0.33
09/03/2016	5.8	Pawnee	OK	7.1	30	X	-	-	1	1	$5	$743,000	0.00
08/23/2011	5.8	Mineral	VA	11	150	-	-	-	1	1	$0	-	-
08/24/2014	6	Napa	CA	26	2300	X	X	X	1	1	$6	$21,000	0.03
01/17/1994	6.7	Northridge	CA	34	82000	-	-	X	1	1	$21,207	$67,780,000	0.03
07/06/2019	7.1	Ridgecrest 7.1	CA	35	99	X	X	-	1	1	$63	$5,200,000	0.00
10/16/1999	7.1	Hector Mine	CA	49	1300	-	-	-	1	2	$0	-	-
02/28/2001	6.8	Nisqually	WA	92	28000	X	X	X	2	2	$7,373	$2,840,000	0.26
04/29/1965	6.7	Puget Sound	WA	120	43000	X	X	X	3	3	$13,576	$223,000	6.09
10/17/1989	6.9	Loma Prieta	CA	160	110000	X	X	X	3	3	$343,775	$11,340,000	3.03
11/03/2002	7.9	Denali	AK	290	53	X	XX	-	3	2	$25,928	$78,000	33.24
11/30/2018	7	Anchorage	AK	330	4300	X	X	-	3	3	$10,878	$150,000	7.25
04/04/2010	7.2	Baja	CA	580	33000	X	XX	XX	4	4	$96,824	$1,330,000	7.28
03/28/1964	9.2	Alaska	AK	2100	10000	-	XX	XX	4	4	$313,450	$2,300,000	13.63

For the purposes of this project, replacement cost estimates are obtained frequently from the HAZUS manual for basic infrastructure such as railroads and bridges (HAZUS table 15.16), utility pipes (HAZUS table 15.17), cost per square foot (*cpsf*) of different building types (HAZUS table 3.6 and 3.7), and *cpsf* of residential garage adjustments (HAZUS table 3.8). Definitions of damage states were also obtained for infrastructure such as roads and bridges (HAZUS 7.1.6) and their corresponding damage ratios (HAZUS tables 15.13, 15.25, and 15.27).

Road costs were calculated separately using base and surface asphalt thicknesses from the Asphalt Paving Association of Iowa (APAI) for different traffic classes and approximate construction costs, displayed in **tables 2** and **3.** Costs for roads of different traffic classes using APAI thickness estimates, asphalt density of 145 lb/ft^3, asphalt costs of $100 per ton (varies greatly due to oil prices), and additional 15% labor, mobilization, and contingency costs. Asphalt depths are doubled for runway calculations using the same class schema. Requirements for traffic classes are found in table 3 and calculations of cost per square foot for each traffic class are found in table 4.

Table 3: Determining traffic class by expected traffic of roads, parking lots, and airports.

Traffic Class	ADT (avg. daily traffic)	Trucks (lifetime)	Parking lots	Airport (lb max gross wt)
2	<200	<7,000	<500 stalls	<7,500
3	200-700	7,000-15,000	>500 stalls	<15,000
4	701-4,500	70,000-150,000	Industrial lots	<30,00
5	4,501-9,500	700,000-1,500,000	-	<60,000

Table 4: Calculations of cost per square foot (cpsf) replacement of each road type.

Traffic Class	Road type	Base (in)	Surface (in)	Total (in)	Cost/sqft
1	Pedestrian walkways: $2.72 if asphalt				
2	Residential	5	1	6	$8.17
3	Residential or collector	5	1.5	6.5	$8.85
4	Collector or arterial	6.5	2	8.5	$11.57
5	Arterial	8	3	11	$14.98

HAZUS table 15.16 provides cost for a full airport runway replacement value. This can be used in cases where a full runway needs replacement without any specifying details, which is rare. In events of high liquefaction impact, such as 1989 Loma Prieta and 2002 Denali, runways needed replacement, but cost of replacement was found in literature, so estimation was unnecessary. These costs can also vary greatly depending on traffic expectations for the associated airport or length of runway. Therefore, more specific calculations for runway *cpsf* can be found using information in tables 1 and 2, ensuring that depths are doubled to account for greater weight of airplanes.

Anything in reconnaissance reports labeled as a general “road crack” or a specified crack width of less than 6 inches was assigned damage value using 6 inches width because it is nearly impossible to replace a very small amount of road. Though a simple fill of road cracks is possible in some cases, this is not possible if underlying aggregate is also cracked or offset a significant amount. This is common in liquefaction cases where more than the first few inches of surface are impacted. Thus, simple fill was not considered as a possibility in these calculations.

Damage costs do not account for value of real estate on which the damage to infrastructure occurred, as our goal was only to assess repair or replace costs. However, costs for repairing or replacing infrastructure differs by location. To account for this, costs were estimated using the HAZUS methodology were also multiplied by the area modification factor (AMF) found in Moselle (2019) of the city in which the damage occurred. If the city where the damage occurred was not found in Moselle (2019), the state’s AMF was used as a cost multiplier.

Damages due to tertiary hazards such as floods or fire caused by liquefaction are included in this database. However, it is not our belief that tertiary hazards were included in consideration of Bird and Bommer (2004) liquefaction damage states. Liquefaction damage cost estimates for the 1994 Northridge event in the category, ‘Buildings’, totaled more than $16M, much of which is attributed to fires likely caused by liquefaction damage. This may occur when gas pipes broke, allowing flammable liquid to spread, and burst water pipes encouraged the fire to spread throughout neighborhoods and damage several residences at a time. However, Bird and Bommer (2004) defined this event’s category as exceeding the damage state threshold for only minor/moderate damage relative to the total event. It is also possible that Bird and Bommer (2004) simply have a higher threshold for what is truly considered liquefaction damage. This can be seen in 1994 Northridge as well where their Utilities and Transportation categories are marked as no damage due to liquefaction, but our database estimates over $3M in Utilities and $1M in Transportation costs due to liquefaction damage. An excerpt from the appendix including all liquefaction damages from the 1994 Northridge earthquake can be found in table 5 to illustrate the liquefaction loss database.

"Municipality" refers to the municipality in which damage occurred, if it is known. "Locale" refers to the general location in which damage occurred, if it is known, such as a neighborhood or landmark. This is especially helpful in cases where the exact location is not known. "Description" gives a short description of damage estimated due to liquefaction, based on report descriptions. "Category" refers to category of infrastructure as generally defined by Bird and Bommer (2004) and outlined in table 6. "Subcategory" refers to the next layer of infrastructure breakdown created for this project and also outlined in table 6. "Cost" refers to 2018 USD estimations of liquefaction damage repair costs, which oftentimes involve replacement of different infrastructure. "Lat" and "Lon" refer to latitude and longitude of specific locations of infrastructure damage if known. "Road_Level" refers to the level of road damaged if the row describes a road damage. The column, "Site", indicates if a row describes damage occurring at a single site ("S") or at multiple sites ("M"). For the purposes of this project, any damage which can be described with a large polyline, such as "2.0 miles of road damaged" or a large polygon, such as "100 pipe breaks across a district" is marked at a multiple-site damage. Additionally, any damage which could be single-site does not have a specific location attached to it is marked as a multiple-site damage. If future projects want to assess LSE, population exposure, or other potential excitation variables at liquefaction damage sites, and include multiple-site damages, the multiple-site damages could be associated with polygons or polylines of their municipality or locale. This would allow potential excitation variables for multiple-sites to be extracted across their corresponding polygons or polylines instead of at specific latitude-longitude coordinates, which is possible for single-site damages.

“Fire” in the final column is given a value of 1 if the damage was caused by a liquefaction-induced fire and a value of 0 if it was caused more directly by liquefaction. Damage by liquefaction-induced fires only occurred in the 1994 Northridge event and the 1989 Loma Prieta event.

The full liquefaction loss database is found in Appendix A. In addition to the full database, we also summarized the liquefaction loss by event in table 2 and compared that to liquefaction intensity measures such as Htot, damage states defined by Bird and Bommer (2004), and liquefaction intensity indices, where subscript “Reconnaissance” refers to reconnaissance-based liquefaction intensity index and “GGLM” indicates global geospatial liquefaction model-based liquefaction intensity index reported by Rashidian and Baise (2020). These intensity measures are summarized in table 2 for all events in which liquefaction damage was expected in order of increasing TLSE. “TLSE” refers to aggregate liquefaction hazard as defined by USGS Ground Failure estimations, the calculation for which was expressed in the Introduction section. “PopExp” refers to estimated population exposure to liquefaction as defined by USGS Ground Failure estimations. “Mw” refers to moment magnitude, as defined in each event by the USGS. This is typically reported in moment magnitude. “Buildings”, “Transportation”, and “Utilities” refer to infrastructure categories as defined by Bird and Bommer (2004). A schema for these categories’ definitions can be found in table 6. In the category columns, “-” indicates no liquefaction damage reported, “X” indicates minor/moderate liquefaction damage relative to overall damage, and “XX” refers to major damage reported relative to overall damage. “2018 Est Liq Costs (thousands)” refers to the estimated liquefaction costs of liquefaction damage in each event using 2018 US dollars. “2018 NOAA Costs (thousands)” refers to total cost estimates of each event adjusted to 2018 US dollars obtained from the NOAA National Centers for Environmental Information. “Percent of Total Costs (%)” indicates approximate percent which liquefaction damage costs account for total earthquake costs.

The final three columns are colored shades of blue corresponding to increasing quartiles. The first quartile of values in each column are assigned a clear background, the second quartile a light blue background, the third quartile a medium blue background, and the fourth quartile a dark blue background.

Non-liquefaction events

In order to ensure that the database is not be biased towards damaging earthquakes or events known to produce liquefaction, we also consider all onshore Canadian, conterminous US, and Mexican events after 1964 with magnitudes greater than 5.0. This totaled 23 non-liquefaction events (NLD) shown in table 7. These events are used specifically in the development of fragility functions. Using a total of 86 events (50 in Bird and Bommer, 2004, 13 unique to this database, and 23 NLD events), fragility functions were developed with different excitation measures of Htot and population exposure.

Table 5: Excerpt from the database describing damages to the Northridge event.

Event	Municipality	Locale	Description	Category	Subcategory	Cost	Lat	Lon	Road Level	Site	Fire
Northridge	Granada Hills	Balboa Boulevard	Soil erosion from broken water mains formed large craters in some streets	Transportation	Road	$395,861			4	M	0
Northridge	Granada Hills	Balboa Boulevard	Several broken water mains (estimate roughly five)	Utilities	Water	$6,862				M	0
Northridge	Granada Hills	Balboa Boulevard	Several broken gas lines (estimate roughly five)	Utilities	Gas	$6,862				M	0
Northridge	Granada Hills	Granada Hills, general	Widespread roadway cracking	Transportation	Road	$3,441			3	M	0
Northridge	Simi Valley	Richardson Highway	47 pipe breaks in area of high liquefaction susceptibility, assign 20% of pipe breakge to liquefaction	Utilities	Water	$12,901				M	0
Northridge	Simi Valley	Rory Lane, Simi Valley	Rory Lane cracking	Transportation	Road	$3,584	34.2697	-118.674		S	0
Northridge	Simi Valley	Christine Avenue, Simi Valley	Christine Avenue cracking	Transportation	Road	$7,941	34.2684	-118.6697		S	0
Northridge	Simi Valley	Kuehner Drive, Simi Valley	Kuehner Drive pavement buckling	Transportation	Road	$1,324				S	0
Northridge	Simi Valley	Christina Avenue, Simi Valley	Masonry wall damage near Christine Avenue	Building	Residential	$833	34.2684	-118.6696		S	0
Northridge	San Fernando Valley	San Fernando Valley, general	1600 Water pipe breaks, attribute 60% to liquefaction	Utilities	Water	$1,317,550				M	0
Northridge	San Fernando Valley	San Fernando Power Plant	Soil to repair 15-foot tall lake embankment	Utilities	Water	$33,831	34.312	-118.492		S	0
Northridge	San Fernando Valley	San Fernando Power Plant	Asphalt to repair 15-foot tall lake embankment	Utilities	Water	$15,293	34.312	-118.492		S	0
Northridge	San Fernando Valley	San Fernando Power Plant	Foundation pier movements for above-ground water conduit	Utilities	Water	$1,372	34.312	-118.492		S	0
Northridge	Los Angeles	Upper Van Norman Lake	~50 meters of rails need replacement	Transportation	Rail	$137,245	34.306	-118.493		S	0
Northridge	San Fernando Valley	San Fernando Valley, general	Gas pipe breaks	Utilities	Gas	$5,490				M	0
Northridge	Santa Clara	Santa Clara, general	Water pipe breakage	Utilities	Water	$47,531				M	0
Northridge	Santa Clarita	Santa Clarita, general	Pavement distress, estimated 100 sq ft replacement	Transportation	Road	$956			2	M	0
Northridge	Santa Clarita	Santa Clarita, general	Significant pipe breakage, estimated 10 pipes broken	Utilities	Water	$13,725				M	0
Northridge	Santa Clarita	Santa Clarita, general	Oil ruptures, at least 3 of 4 due to liquefaction	Transportation	Gas	$4,117				M	0
Northridge	Santa Clarita	Santa Clarita, general	Water storage tank collapse	Utilities	Water	$1,464,134				S	0
Northridge	Los Angeles	Marina Del Ray	"Some pipe breakage", estimate five pipes broken	Utilities	Water	$6,451				M	0
Northridge	Redondo Beach	King Harbor Mole B	"Almost every pipe behind the failed wall broke": Estimated five water pipe breaks	Utilities	Water	$6,451	33.848	-118.399		S	0
Northridge	Redondo Beach	King Harbor Mole B	"Almost every pipe behind the failed wall broke": Estimated one gas pipe break	Utilities	Gas	$1,290	33.848	-118.399		S	0
Northridge	Los Angeles	Joseph Jensen Filtration Plant	85-inch diameter pipe burst (estimate cost equivalent to five typical pipe breaks)	Utilities	Water	$6,451	34.315	-118.497		S	0
Northridge	Redondo Beach	King Harbor Mole B, Yacht Club	2 buildings distorted from settlemnt	Building	Commercial	$150,319	33.85	-118.396		S	0
Northridge	Los Angeles	Joseph Jensen Filtration Plant	Parking lot pavement cracking	Utilities	Water	$423,533	34.315	-118.497		S	0
Northridge	Redondo Beach		Seaside Lagoon	Building	Commercial	$5,083,800	33.845	-118.395		S	0
Northridge	Redondo Beach	King Harbor Mole B	King Harbor Mole B Parking ruined	Transportation	Port	$397,062	33.85	-118.397		S	0
Northridge	Redondo Beach	King Harbor Mole B	Many automobiles damages, estimate 2018 costs of 10 cars sustaining $5,000 of damage each	Transportation	Port	$50,000	33.85	-118.397		S	0
Northridge	Los Angeles	Port of LA	Port of LA dock, cranes, power, ground cracking	Transportation	Port	$84,730	33.737	-118.265		S	0
Northridge	Santa Monica	Santa Monica, general	Santa Monica earthquake-related fires, assume only 50% due to liquefaction related fires, fire department estimate so addition of contents value not needed	Building	Residential	$711,640				M	1
Northridge	Santa Monica	Santa Monica, general	Santa Monica earthquake-related fires, assume only 50% due to liquefaction related fires, fire department estimate so addition of contents value not needed	Building	Commercial	$304,988				M	1
Northridge	Los Angeles	Pacoima and Granada Hills, general	Pacoima and Granada Hills earthquake-related fires, assume only 50% due to liquefaction related fires, LAFD estimate so addition of contents value not needed	Building	Residential	$7,349,703				M	1
Northridge	Los Angeles	Pacoima and Granada Hills, general	Pacoima and Granada Hills earthquake-related fires, assume only 50% due to liquefaction related fires, LAFD estimate so addition of contents value not needed	Building	Commercial	$3,149,873				M	1

Table 6: Schema and descriptions for identifying categories and subcategories in the database.

Category	Subcategory	Description	ADT (avg. daily traffic)	Trucks (lifetime)	Parking lots	Airplane maximum pounds gross weight (double costs for thicker asphalt)
Building	Residential	Single Family Dwelling, Manufactured Housing, Multi-Family Housing, Insitutional Dormitory, Nursing Home				
	Commercial	Retail Trade, Wholesale Trade, Personal and Repair Services, Hospital, Medical Office/Clinic, Entertainment & Recreation, Theaters, Parking Garages Professional/Technology/Businesss Services, Banks				
	Industrial	Factories, Warehouses, Food/Drugs/Chemicals research/production factories or college laboratories, Metals/Minerals Processing, High Technology factories or college laboratories				
	Institutional	Religious buildings, Government General Services or Emergency Response, Schools, Libraries, Colleges, Universities properties				
Transportation	Road_1	Sidewalk or pedestrian walkway				
	Road_2	Residential or collector	<200	<7,000	<500 stalls	<7,500
	Road_3	Residential or collector	200-700	7,000-15,000	>500 stalls	<15,000
	Road_4	Collector or arterial	701-4,500	70,000-150,000	Industrial lots	<30,00
	Road_5	Arterial	4,501-9,500	700,000-1,500,000	-	<60,000
	Road_Bridge	Any bridge over which automobiles travel				
	Rail	Train tracks				
	Rail_Bridge	Any bridge over which trains travel				
	Airport	All structures besides utilities on airport properties (runways and buildings included)				
	Port	All structures besides utilities on commercial port and harbour properties				
Utilities (Lifelines)	Water	Water pipe or sewer pipe breaks or replacements, or damage to water treatment facility, soil embankments surrounding water, levees along rivers, or Canals feeding crops				
	Gas	Gas pipe or oil pipe breaks or replacements				
	Electric	Power lines				
	Agriculture	Crops on agricultural fields				

Table 7: 23 Non-liquefaction events, sorted by increasing Htot. The state label "MX" indicates Mexico.

Date	Mw	Name of Event	State	Htot	PopExp
3/21/69	6	Baja California-Sonora border region	MX	0	0
8/17/91	6	Northern California	CA	0.072	0
4/20/02	5.3	New York	NY	0.093	7
8/13/78	5.1	12km S of Santa Barbara	CA	0.2	150
4/23/92	6.1	17km NNE of Thousand Palms	CA	0.39	320
8/7/66	6.5	173km SE of Estacion Coahuila, Baja California	MX	0.39	240
11/23/84	6.1	Central California	CA	0.42	0
5/17/93	6.1	46km E of Big Pine	CA	0.54	0
5/25/80	6.1	Central California	CA	0.69	0
5/25/80	6	Long Valley area, California	CA	0.7	0
5/27/80	6.2	Central California	CA	0.87	1
3/31/20	6.5	70 km W of Challis, Idaho,	ID	0.87	0
7/8/86	6	6km SSW of Morongo Valley	CA	1.2	630
7/21/86	6.4	Central California	CA	3.4	20
5/25/80	6.1	Central California	CA	4	0
3/28/75	6.1	southern Idaho	ID	6.4	4
5/15/20	6.5	56 km W of Tonopah, Nevada,	NV	11	0
11/24/87	6.2	17km WNW of Westmorland	CA	15	200
4/24/84	6.2	Northern California	CA	19	21000
10/28/83	6.9	southern Idaho	ID	23	56
9/21/93	6	Oregon	OR	29	32
4/9/68	6.6	5km NNE of Ocotillo Wells	CA	90	11000
10/15/79	6.4	10km E of Mexicali, Baja California	MX	100	18000

4. Fragility function methodology

Fragility functions were calculated from damage states primarily following the Porter (2020) methodology. The "bounding-failure excitation option is utilized, where at least one specimen did fail, at least one specimen did not fail, and the peak excitation to which each specimen was subjected is known, but not known at exactly what excitation they each failed. In our case, the excitation measure refers to Htot, or aggregate liquefaction hazard. Our "specimen" reaching failure is represented by an event surpassing a damage state threshold.

The maximum likelihood estimation (MLE) option of determining fragility function parameters on a lognormal distribution as described by Baker (2015) and Porter (2020) was used.

First, the data was sorted into bins where the proportion of events which reached each damage state could be determined. Cutoff levels for each bin were determined by placing the numbers 1 through 10^n on a log-scale then dividing evenly into 3*n bins. The minimum of bin 0 was adjusted from 1 to 0 include all events with Htot of between 0 and 1. While a plurality of events exists in Bin 0, it is likely not necessary to divide this bin further as the measure of excitation difference is very small from 0 to 2.2. Events on the border of two bins are included in the bin of lower value.

A theoretical probability of failure was determined at the x value representing the average excitation measure for each bin using the lognormal cumulative density function (CDF) in equation 3. Starting parameters, sigma and beta, are estimated visually, but are adjusted via MLE.

$$p_i = \Phi\left(\frac{\ln(r_i/\theta)}{\beta}\right) \tag{3}$$

Next, the likelihood, or probability density function (PDF), is determined for each bin of observing the number of specimens which failed based on the theoretical probability of failure (CDF) in equation 4.

$$P[F_i = f_i] = \frac{n_i!}{f_i!(n_i - f_i)!} \cdot p_i^{f_i} \cdot (1 - p_i)^{n_i - f_i} \tag{4}$$

Then, the product of likelihood probabilities of each bin is maximized while adjusting sigma and beta in equation 5. The resulting sigma and beta would be used to construct and plot a CDF continuously along the x-axis known as a “fragility function”, which represents the probability of exceeding the examined damage state at each particular excitation measure.

$$L(\theta, \beta) = \prod_{i=1}^{m_i} P[F_i = f_i] \tag{5}$$

For the Transportation plots, it became apparent that fragility functions for the first and second damage states crossed. This is problematic because it implies that, for high excitation measures, exceeding the threshold for the second damage state is more probable than exceeding the threshold for the first damage state, which is not possible. Following the most “proper” option of preventing fragility functions from crossing in Porter (2020) is to use MLE again, this time deriving the fragility functions simultaneously with a single common beta and separate medians for each damage state. This is accomplished by maximizing PDFs across all damage states in equation 6.

$$O = \prod_{d=1}^{m} \prod_{i=1}^{s} P_Y(y) \tag{6}$$

Lastly, beta and theta adjustments were explored for cases with few specimens per bin. Following the appropriate MLE method, the beta was adjusted using equation 33, where B represents the MLE-derived

Beta and B_u represents 0.25, followed by the adjustment for theta of each damage state in equations 7, 8, and 9.

$$\beta' = \sqrt{\beta^2 + \beta_u^2} \tag{7}$$

$$\bar{r} = \frac{\sum_{i=1}^{N_i} r_i \cdot n_i}{\sum_{i=1}^{N_i} n_i} \tag{8}$$

$$\theta' = \bar{r} \cdot \left(\frac{\bar{r}}{\theta}\right)^{(-\beta'/\beta)} \tag{9}$$

5. Results

Figure 3 presents the liquefaction loss database in terms of three infrastructure categories: buildings, transportation, and utilities. Five events had observed liquefaction, but no infrastructure damage. 10 events had liquefaction infrastructure damage under $100M. Only two events, 1964 Alaska and 1989 Loma Prieta, had liquefaction damages over $100M, which were also over $300M.

Six of the 12 events with liquefaction damage had less than 1% of total earthquake damage costs attributed to liquefaction. Three of those six have transportation costs which make up more than 90% of total liquefaction damage costs. From this, we can conclude that transportation costs should be considered as a primary driver of liquefaction damage in earthquakes.

Figure 3 shows that transportation damage composes a majority of estimated damage costs in most large events. Figure 3 also shows that Utilities generally makes up a small proportion of damages, excluding the 2010 Baja event. In this earthquake, canals and agriculture (which are categorized as Utilities) were heavily impacted in a farming region. This figure also reveals how infrequently buildings are heavily impacted by liquefaction. However, for an event such as 2018 Anchorage, a few large, expensive buildings on soil susceptible to liquefaction can cause disproportionally more loss to buildings than to surrounding roads and utilities. Much of the Buildings cost for 1994 Northridge can be attributed to liquefaction-induced fires. The relationship between liquefaction-induced fires and damage to the Buildings category is a possibility to be explored in future work.

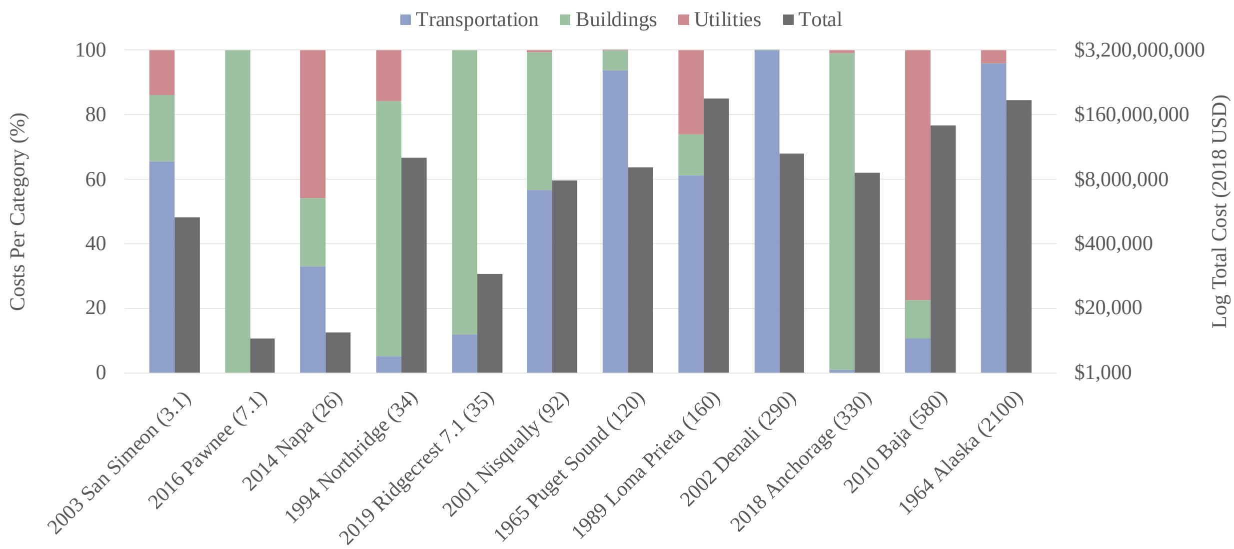


Figure 3: Percentages of the total costs by category and total cost for each event, sorted from left to right by increasing Htot. Five events have no infrastructure damage recorded as a result of liquefaction and are not included in the figure.

In figures 4 and 5, liquefaction loss is plotted against Htot and Population exposure. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with Htot less than 1 have been rounded up to 1 for ease of viewing on an x-log scale. Generally positive trends can be seen in both cases. Figure 5, which shows loss versus population exposure, shows more variance on the x-axis. One point which is improved greatly by using population exposure instead of Htot is the point representing the 2003 San Simeon event. In figure 4, it is the point at Htot of 3.8 with total liquefaction costs over $1M and appears to be an outlier. After adjusting for population exposure, it appears to shift more towards the center of the trend. In contrast, three points of low to medium Htot (2001 Pawnee, 2002 Denali, and 2019 Ridgecrest) have a much lower population exposure and appear to fit the trend less well in figure 5.

Although not included in these plots, the NLD events summarized in Table 7 have Htot all below 100 with only two events between 30-100. These events would provide additional points between 1 and 100 and would be consistent with the trend observed in Figure 4. The NLD events have two events with PopExp between 10,000 and 21,000. If added to Figure 5, the NLD events would provide further evidence that the trend is not as clear with many events with no liquefaction costs and high PopExp.

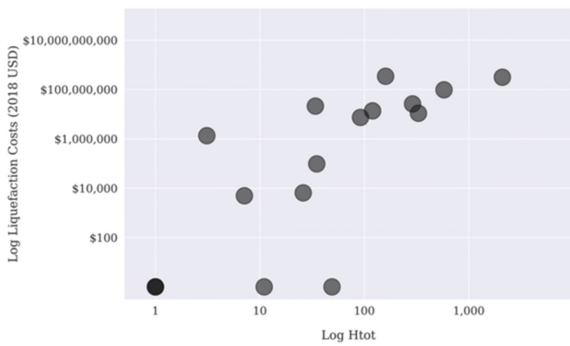


Figure 4: Log **total** liquefaction costs versus log **Htot**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with Htot less than 1 have been rounded up to 1 for ease of viewing on an x-log scale.

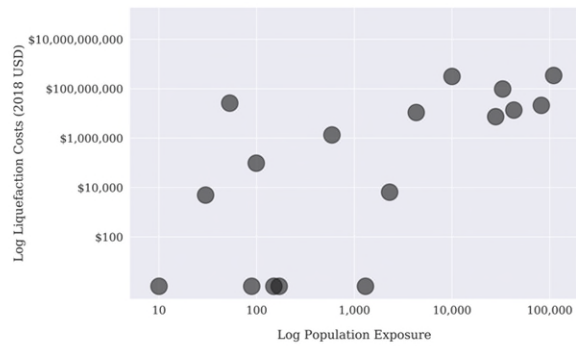


Figure 5 : Log **total** liquefaction costs versus log **population exposure**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with PopExp less than 10 have been rounded up to 10 for ease of viewing on an x-log scale.

Losses due to liquefaction by infrastructure category versus Htot and population exposure were then extracted for buildings (figures 6 and 7), transportation (figures 9 and 10), and utilities (figures 11 and 12). Population exposure is a proxy for infrastructure exposed to a hazard. This was expected to improve the relationship, at least visually, between estimated liquefaction costs and excitation measure for all categories.

For the 17 events examined in detail, the building loss compared with population exposure in figure 7 has a linear correlation for events with more than $5,000 of liquefaction building damage. Some outliers are the 2014 Napa event which has a moderate population exposure of 2300 but a low liquefaction damage to buildings of less than $10,000 and the 1964 Alaska event, which has no building damage attributed to liquefaction. Similarly, the 5 non-liquefaction-damage events have moderate population exposures but no damage.

LSE values slightly above the threshold for inclusion were seen in areas of moderate to high population density for these events, leading to a moderate population exposure values. If the threshold for a cell's LSE value to be included in the Htot summation were raised, the summation would only include cells with greater probabilities of liquefying. Though this reduce the Htot and PopExp for all earthquakes, it is expected to reduce Htot and PopExp values most for events which cover a wide area with light to moderate shaking, such as in the 2014 Napa event. This is expected to improve our fit.

For example, in Figure 1, the lightest color indicating LSE on the map represents probabilities in the range of 0.5% to 1%. A new proposed threshold of 1% would eliminate all cells of the lightest color from inclusion in the summation. As seen in Figure 8, which represents the number of cells in each LSE interval for the 2001 Nisqually event, this composes more than another 3,000 cells which would be removed from the summations of Htot and PopExp.

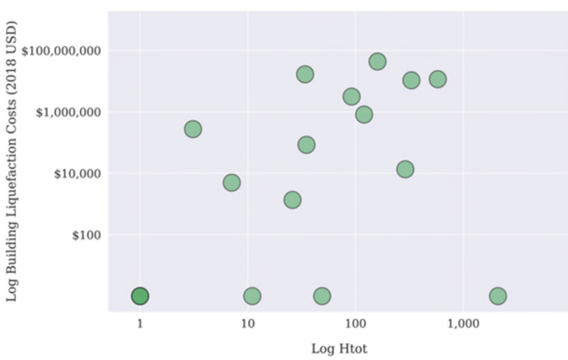


Figure 6: Log **building** liquefaction costs versus log **Htot**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with TLSE less than 1 have been rounded up to 1 for ease of viewing on an x-log scale.

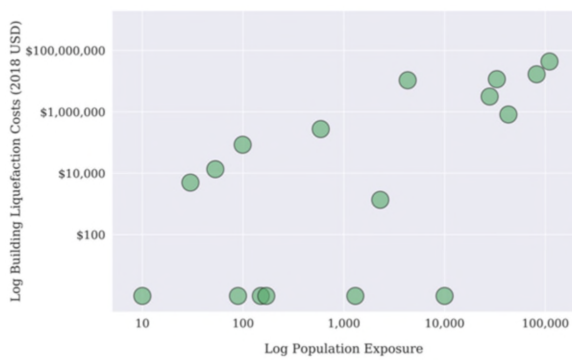


Figure 7: Log **building** liquefaction costs versus log **population exposure**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with PopExp less than 10 have been rounded up to 10 for ease of viewing on an x-log scale.

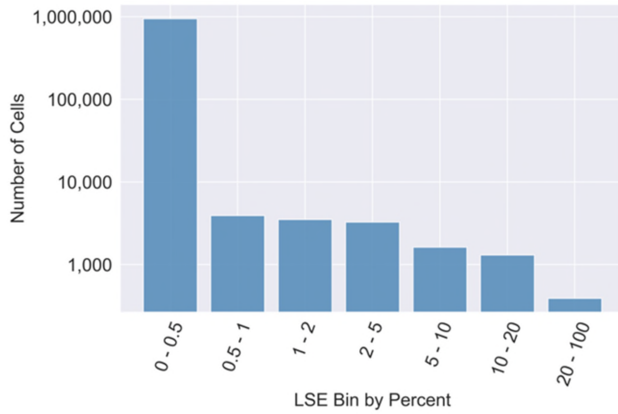


Figure 8: Number of cells within each LSE bin for the 2001 Nisqually event.

Utility loss of 2003 San Simeon, 1994 Northridge, and 1989 Loma Prieta appear to be greatly improved when accounting for population exposure compared with only considering Htot. Utilities exist primarily in areas of high population so adjusting for the population exposed to a hazard is expected to improve the relationship of recorded loss versus hazard. The 1964 Alaska event is another clear example of this. When examining only Htot in Figure 9, the estimated area exposed to liquefaction, this event is calculated to have had a higher excitation value by far than the next closest event, 2010 Baja. However, after adjusting for population exposure in Figure 10, the 1964 event has an excitation measure closer to that of 2010 Baja and slightly less than the 1989 Loma Prieta event, which caused more liquefaction damage to utilities. This is consistent with the observations of damage as the 1989 Loma Prieta event has a higher cost of recorded liquefaction damage.

While utilities loss versus population exposure appears at first glance to show a much better fit in Figure 10 than building loss versus population exposure, this may be in part due to no Utilities liquefaction damages recorded in less-populated regions. Only one event with population exposure less than that of the 2014 Napa event has associated utilities damage due to liquefaction. Three events (2016 Pawnee, 2019 Ridgecrest, and 2002 Denali) have recorded liquefaction damages, but none in the Utilities category. It is possible that it was easier to identify and record liquefaction damage to Utilities in more-populated areas.

However, we also see a similar pattern to the Buildings category where some events have moderate population exposure but low or no liquefaction damage to the Buildings category. In the Utilities category, it is also expected that establishing a higher LSE threshold for inclusion in the summation will lower both the Htot and PopExp values for these events. This would again have the effect of consolidating events of low and moderate excitation measures towards the lower end of the x-axis, which is more consistent with observations.

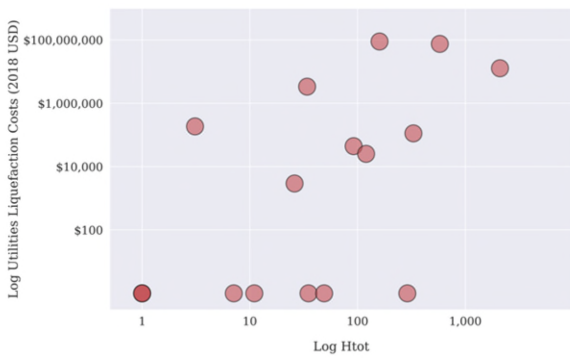


Figure 9: Log **utilities** liquefaction costs versus log **Htot**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with Htot less than 1 have been rounded up to 1 for ease of viewing on an x-log scale.

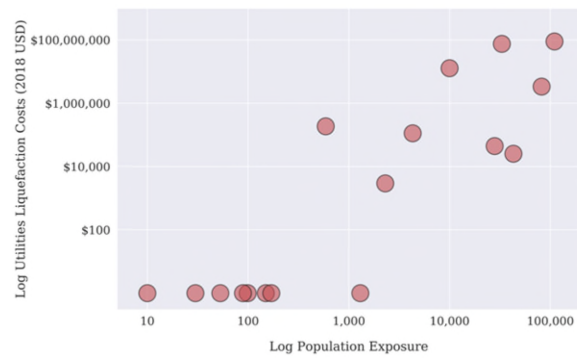


Figure 10: Log **utilities** liquefaction costs versus log **population exposure**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with PopExp less than 10 have been rounded up to 10 for ease of viewing on an x-log scale.

The last category, Transportation, does not improve significantly when accounting for population exposure in Figure 12 in comparison with only aggregate liquefaction hazard in Figure 11. In some cases, expensive pieces of Transportation infrastructure, such as bus or train stations, are expected in areas of high population. However, this is not always the case, as many railways, bridges, and airports can exist far from populated areas.

For example, the 2002 Denali event was calculated to have an aggregate liquefaction hazard value of 290, a population exposure of 53, more than $25M in damages, primarily to an airport, which falls under the Transportation category. In Figure 11, both its Htot and liquefaction damage cost values are considered in the middle of the range. However, when accounting for population exposure, it is shifted far the low end of excitation measures.

Similarly, the 1964 Alaska event has both the highest Htot value and the highest total cost of liquefaction damage to transportation. But after accounting for population exposure, it is shifted toward the center of the excitation measure range, and the point no longer fits the data as well. It is thus not always expected that comparing transportation costs to population exposure will yield a better correlation than simply expected area exposed to liquefaction hazard.

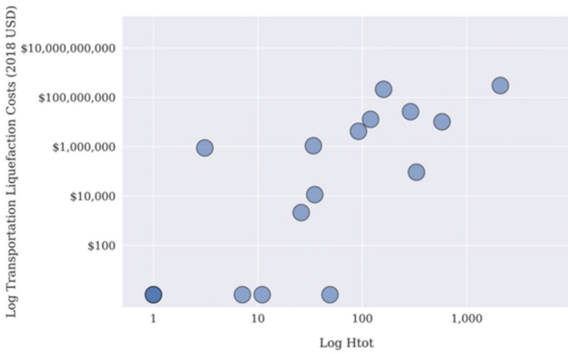


Figure 11: Log **transportation** liquefaction costs versus log **Htot**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with Htot less than 1 have been rounded up to 1 for ease of viewing on an x-log scale.

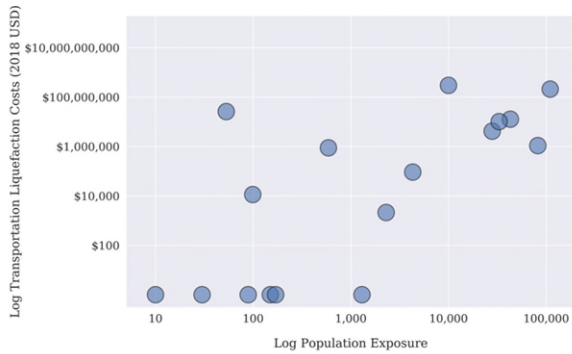


Figure 12: Log **transportation** liquefaction costs versus log **population exposure**. Events with no recorded liquefaction damage have been assigned a value of $1 to be included on a y-log scale. Events with PopExp less than 10 have been rounded up to 10 for ease of viewing on an x-log scale.

In summary, we recommend estimating Transportation liquefaction costs based on Htot and estimating Building and Utilities liquefactions costs based on population exposure. However, if we had included the NLD events, Population exposure would have been more problematic with additional events with high PopExp and zero loss across all categories. We also recommend using a higher threshold for LSE when calculating aggregate statistics of 0.01 instead of 0.005 for individual cells. Transportation costs compose the majority of liquefaction cost data in this database. Therefore, if data is not broken up into these categories and to prevent bias from not including NLD events, we recommend estimating liquefaction loss based on Htot.

Fragility Functions

In the next section, expected probabilities of exceeding the thresholds for different damage states are calculated using events from the Bird and Bommer (2004) dataset and unique events from this dataset, which totaled 63 of the world's more damaging earthquakes. The liquefaction loss database developed for this project as summarized in the Appendix and in Tables 1 and 2 used events that were selected specifically because liquefaction was reported. This is known as "sample selection bias" caused by only choosing non-random data for an analysis. By complementing the existing database with non-liquefaction-damage (NLD) events as summarized in Table 7, we seek to reduce this bias. This bias can continue to be reduced by including more NLD events by setting a lower magnitude threshold for inclusion. However, we start to see a marginal effect of adding more earthquakes as lower magnitude events will generally have lower Htot values and will all be grouped together in the lowest class of Htot events.

In order to ensure fragility functions are not biased towards damaging earthquakes near major cities or events known to produce liquefaction, we consider all onshore Canadian, conterminous US, and Mexican events after 1964 with magnitudes greater than 5.0. This totaled 23 NLD events shown in Table 7. Using a total of 86 events (50 in Bird and Bommer, 2004, 13 unique to my database, and 23 NLD events), fragility functions were developed with different excitation measures of Htot and population exposure, as shown in Tables 8 and 10, respectively.

As seen in Figures 13 and 14, the additional non-liquefaction events have low aggregate liquefaction hazard values (Htotmax=100) and low to moderate population exposure values (PopExpmax=18,000). In Figures 4-12, they would have added points to the lower left corners of the plot. The exception to this is the two events with high Htot (>50) and three events with high population exposure (>10,000). It is expected that the increased number of points which fall in the expected range will improve the overall fits. It is also expected that sample selection bias is reduced in these plots by including the additional NLD events. Overall, inclusion of the NLD events would improve the trends with Htot and hurt the trends with PopExp.

These NLD events are expected to impact expected probabilities of failure for events with low aggregate liquefaction hazard values when we calculate fragility functions. More specifically, because these non-liquefaction events were all assigned damage state of 0 for all three categories, they were expected to decrease the probability of events exceeding damage state thresholds for low TLSE events.

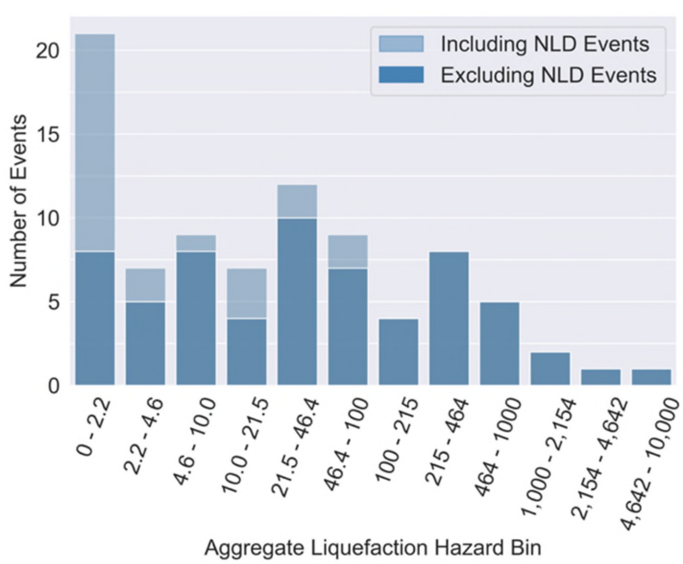


Figure 13: Number of events per aggregate liquefaction hazard (TLSE) interval including 50 events from Bird and Bommer (2004), 13 unique events from the discussed database, and 23 additional non-liquefaction-damage (NLD) events in North America. The 23 NA events are shown as having been added separately as fragility functions are constructed before and after their inclusion.

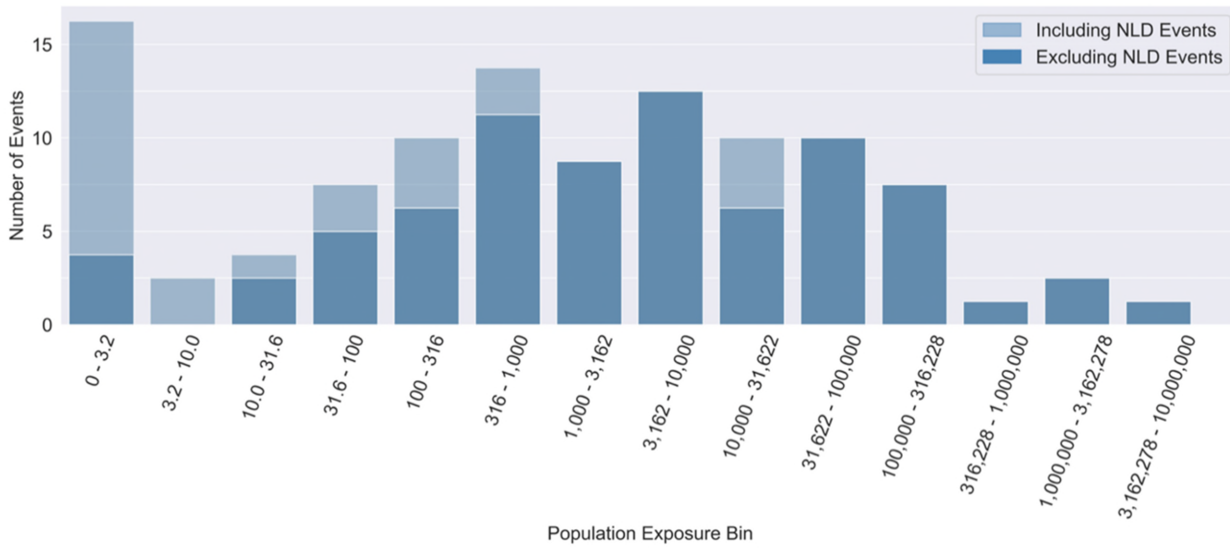


Figure 14: Number of events per aggregate population exposure interval including 50 events from Bird and Bommer (2004), 13 unique events from the discussed database, and 23 additional non-liquefaction-damage (NLD) events in North America. The 23 NA events are shown as having been added separately as fragility functions are constructed before and after their inclusion.

In addition to evaluating TLSE and population exposure versus liquefaction loss, we also converted each event into damage states based on the Bird and Bommer (2004) schema as presented in Table 8. This allowed parameters for fragility functions to be calculated for this dataset. Fragility functions result in cumulative density functions (CDFs) which estimate the probability of exceeding damage state thresholds at different excitation measures.

Table 8: Definitions of damage states according to Bird and Bommer (2004).

Damage State (DS)	Definition
0	Liquefaction not reported, or reported but no mention of damage
1	Minor or moderate liquefactiondamage reported, relative to overall damage
2	Major liquefaction damage reported relative to overall damage

Fragility function parameters were developed by following the preferred strategy for Type-B data in Porter (2020), as discussed in the methodology section, with damage states defined by Bird and Bommer (2004) in Table 8. Function parameters were found both before and after including the 23 NLD events. The 23 NLD events are assumed to exist in the lowest damage state, DS=0, for all categories. The intervals used to establish bins for the fragility functions and the number of events contained within each bin can be viewed in Figures 13 and 14. Two concerns arose from these constructions.

First, it was clear from the plots in table 9 that CDFs for damage states DSs 1 and 2 crossed for the transportation category at high excitation measures. This implies that at high excitation measures, the functions predict a higher probability of exceeding the threshold for DS 2 than for DS 1. By definition, for any experiment where damage states are involved, the threshold for DS 1 should be exceeded before or at the same time as the threshold for any higher DS is exceeded. A correction to account for cases where this occurs is provided in Porter (2020) and was followed as described in the methodology section.

Second, it was observed that some of the aggregate liquefaction hazard intervals used to construct fragility functions, seen in Figure 12, had fewer than five specimens, and are thus under-representative of the data's true relationship, especially at higher excitation measures. Porter (2020) also provides a method of adjusting the parameters for this concern, which is explained in the methodology section. Plots are shown in Figure 12 before and after correcting function parameters for possible under-representation using descriptors "No Parameter Correction" and "Including Parameter Correction".

Fragility functions show large changes when correcting for crossed CDFs. However, they show small change when correcting for small number of observations. Perhaps this suggests that the second correction is not needed. Additionally, the functions change significantly when including the additional 23 North American events for the first damage state in the first half of the excitation measure range. This makes sense intuitively because all additional North American events exist in the first six of 12 bins. This shift indicates that we are reducing bias towards only selecting events with liquefaction damage.

Damage state 2 changes will be inherently more challenging to interpret visually because of their very small probabilities of failure in the first half the excitation measure range. In almost all of these plots we see gradually increasing CDFs.

Table 9: Fragility functions for damages in categories of Buildings (B), Utilities (U), Transportation (T), and Transportation line-cross-adjusted (TLCA).

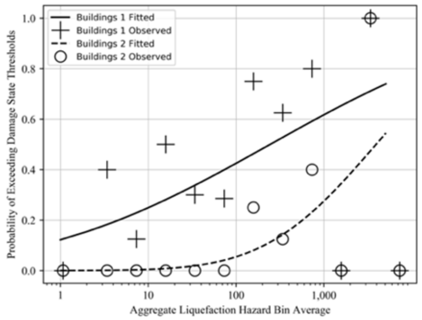
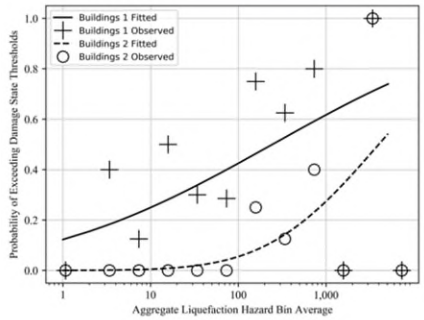
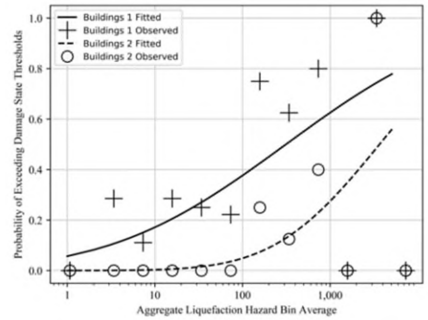
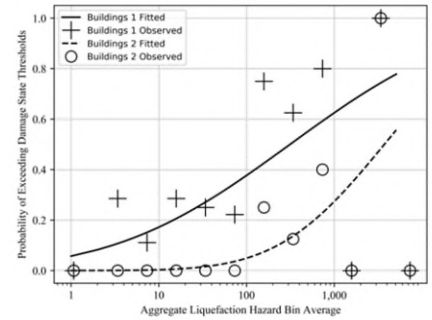
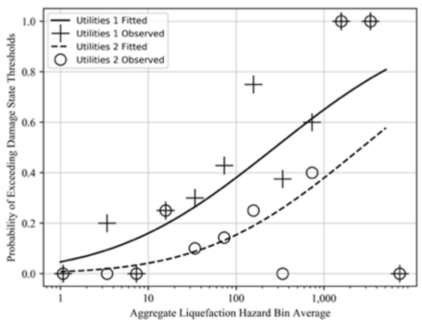
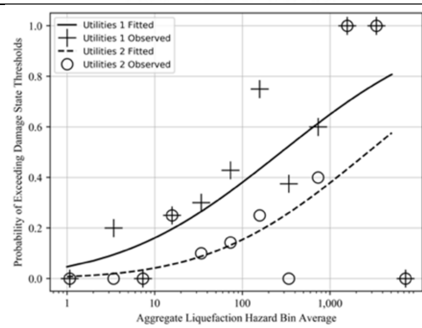
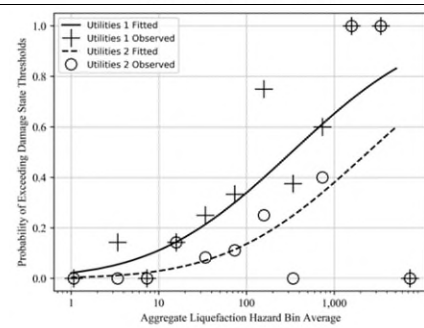
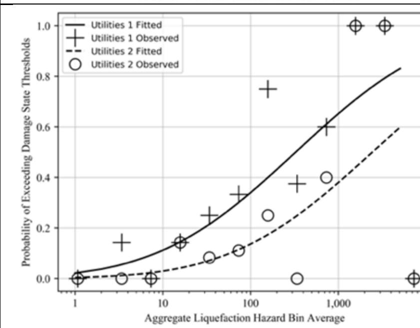
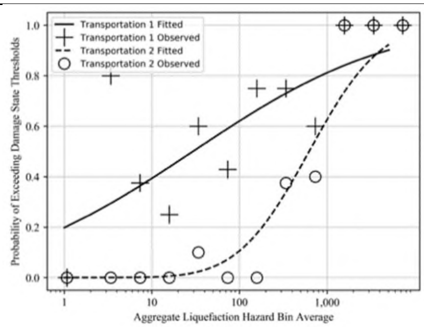
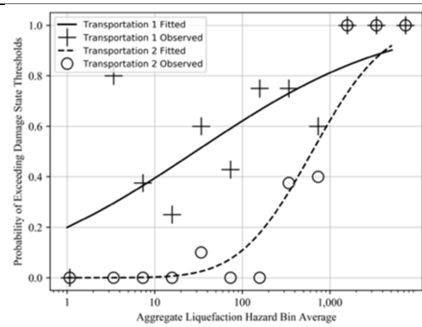
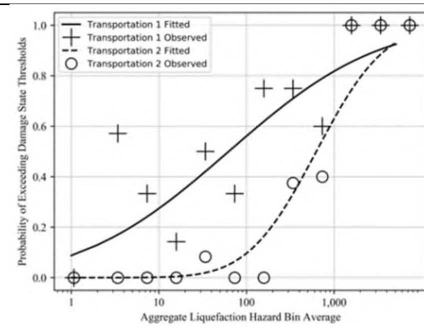
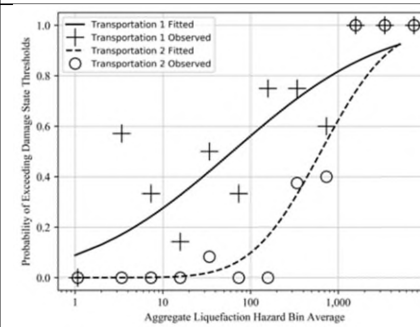
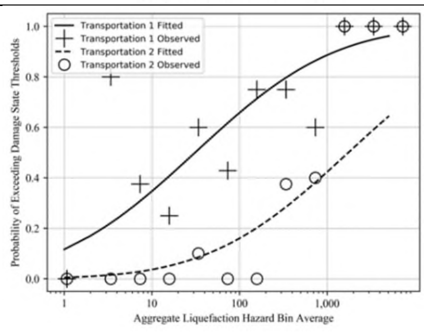
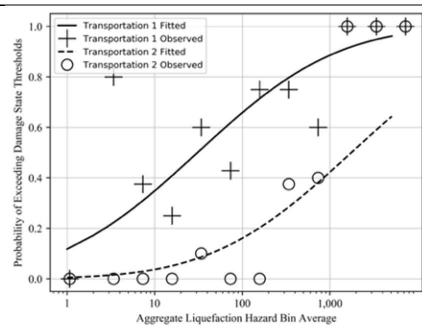
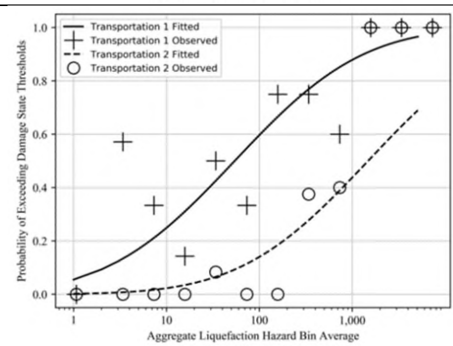
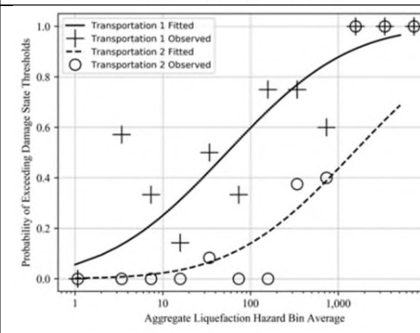
	Not including additional 23 Non-liquefaction-damage Events		Including additional 23 Non-liquefaction-damage Events	
	No Parameter Correction	Including Parameter Correction	No Parameter Correction	Including Parameter Correction
B				
U				
T				
T, LCA				

Table 10: Parameter values resulting from fragility function construction. Parameters for Damage State 1 are marked with clear cells while parameters for Damage State 2 are marked with blue cells. When adjusting for the line-cross in transportation plots, only one dispersion value (Beta) was determined for both damage states.

		Excluding Additional 23 Non-liquefaction-damage Events				Including Additional 23 Non-liquefaction-damage Events			
		No Beta Correction		With Beta Correction		No Beta Correction		With Beta Correction	
	Damage State	Theta	Beta	Theta	Beta	Theta	Beta	Theta	Beta
Buildings	1	245.29	4.72	245.17	4.72	314.02	3.63	314.16	3.64
	2	3940.34	2.29	3997.56	2.31	3671.18	2.17	3736.13	2.19
Utilities	1	278.26	3.34	278.09	3.35	327.16	2.86	327.46	2.87
	2	2715.07	3.23	2731.83	3.24	2435.12	2.91	2455.37	2.92
Transportation	1	29.42	3.99	29.28	4	62.78	3.06	62.48	3.07
	2	624.24	1.47	629.53	1.49	627.72	1.41	636.48	1.43
Transportation, line cross adjusted	1	31.16	2.88	30.88	2.89	54.4	2.50	53.98	2.51
	2	1751.01		1761.7		1485.69		1498.76	

After correcting for crossed fragility functions in the transportation category, it was clear that the adjustment was preferred and is considered more acceptable. Furthermore, we know intuitively that including NLD events reduces bias towards events with damage for low-excitation values.

The correction for few specimens appears not to impact parameter values by more than 1% in any of our calculations, as seen in table 5. In comparison, adding the 23 no-liquefaction-damage events changed the parameters by more than 20% in some cases, also seen in table 5. The correction for under-representative data can be thus seen as an extraneous, unnecessary step, especially considering that adjusting the parameters can cause the fragility function not to pass through the data well (Porter, 2020). Parameters calculated without the correction to be preferred. The preferred fragility functions are displayed in Figure 15, which include the 23 no-liquefaction-damage events, no correction for few specimens, and the transportation category is corrected for the lines which cross.

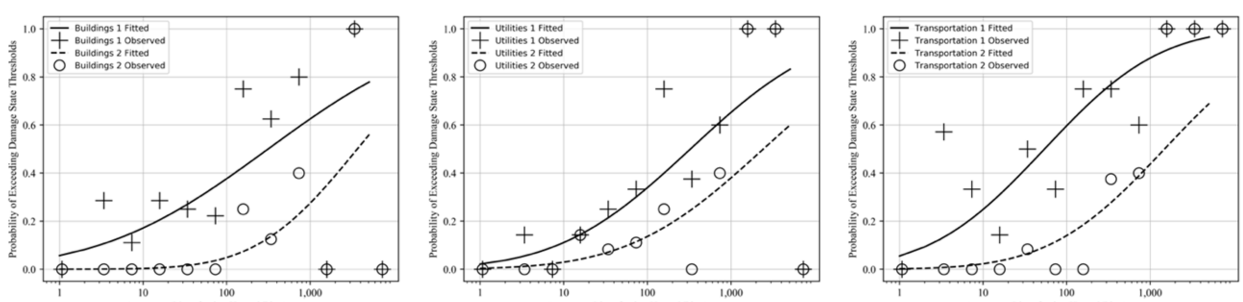


Figure 15: Preferred fragility function results, including 23 no-liquefaction damage events, no few-specimen correction, correcting transportation category for lines crossed.

Similarly, fragility functions were constructed using population exposure as the excitation measure in Table 11 with corresponding parameters in Table 12. These functions appear quite different than the fragility functions developed using Htot. One clear difference is that is that the functions constructed for the Buildings category cross, but the functions constructed for the Transportation category do not. The adjustment for crossed lines is shown beneath each original Buildings plot in Table 11.

It is also clear that in comparison with earlier fragility functions, the probability of exceeding DS 2 remains low for all moderate population exposures then rises quickly as population exposure reaches high values. This can be interpreted as a very low probability of events exceeding DS 2 until the population exposure is high, then the probabilities rise quickly. This may be a better result for systems such as PAGER which benefit from a higher confidence that an event will exist in a particular damage state.

As seen in Table 11, adding NLD events mostly results in increasing the number of events within low to moderate excitation measure bins. In addition to expecting this to reduce bias for the fragility functions at low excitation values, we expect this to decrease the probabilities of exceeding damage states at low excitation measures. As seen in Table 11, this results in a more distinct rise in probabilities of exceeding damage states in the moderate to high excitation measure range. This may also be interpreted as improving the result for systems such as PAGER.

Table 11: Fragility functions for damages in categories of Buildings (B), Buildings line-cross-adjusted (B, LCA), Utilities (U), and Transportation (T) using population exposure.

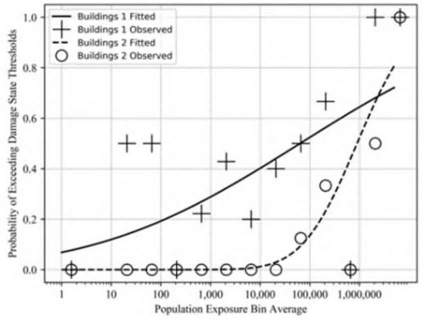
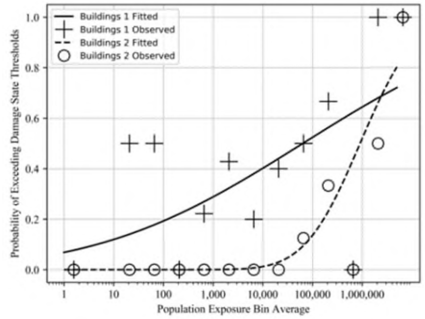
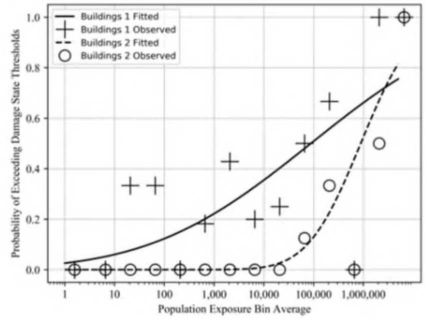
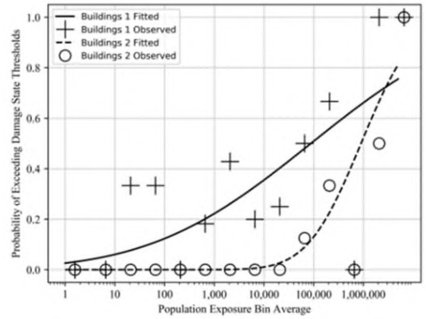
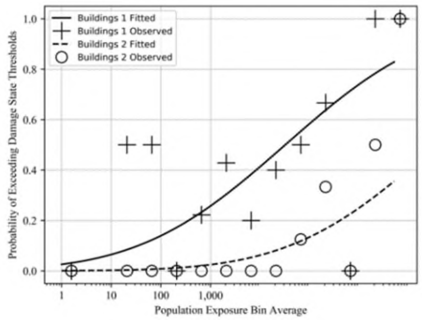
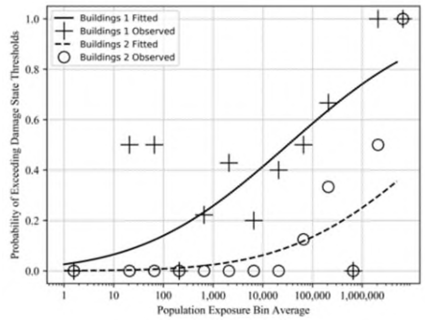
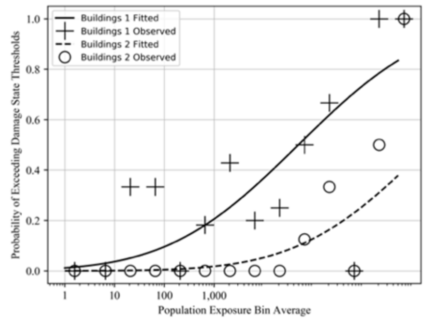
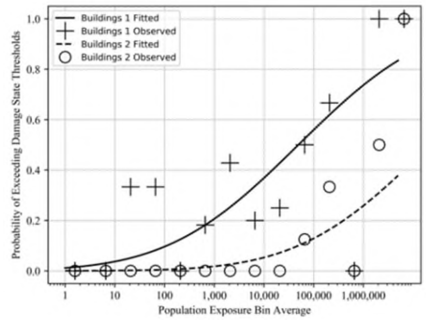
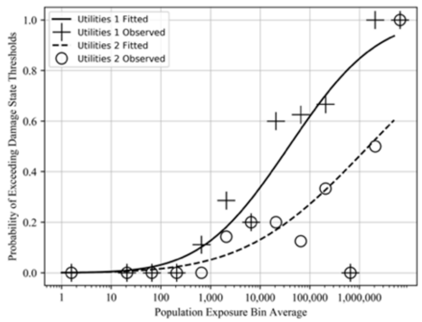
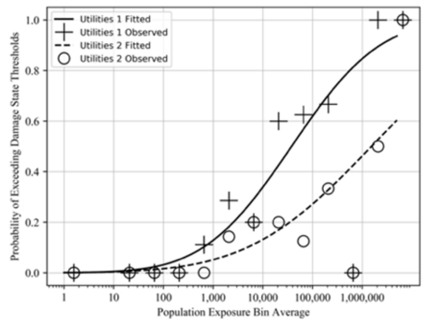
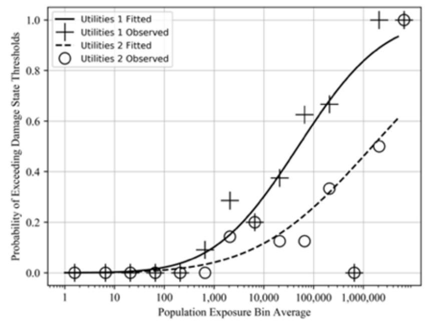
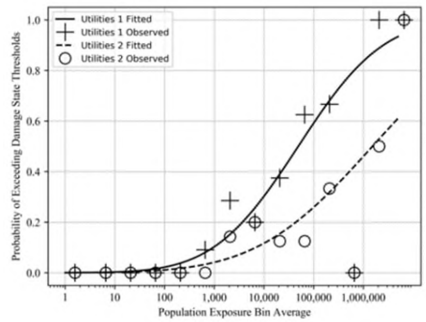
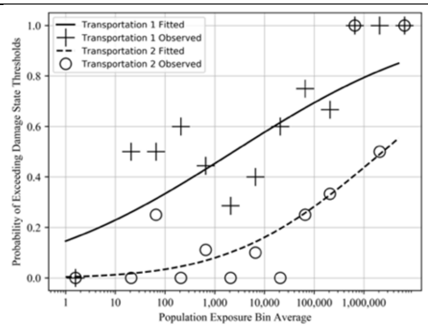
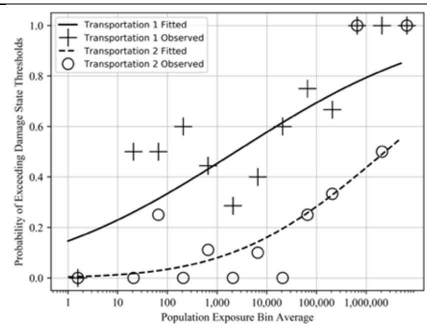
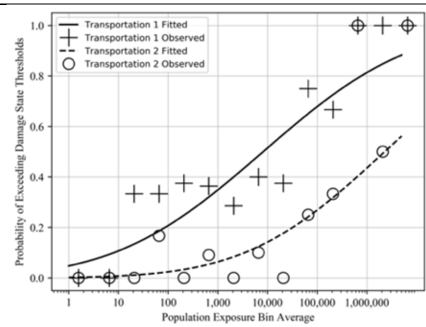
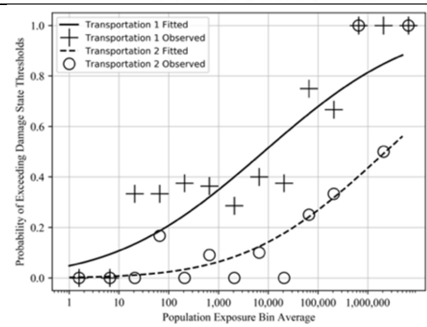
	Not Including Additional 23 Non-liquefaction-damage Events		Including Additional 23 Non-liquefaction-damage Events	
	No Parameter Correction	Including Parameter Correction	No Parameter Correction	Including Parameter Correction
B				
B, LCA				
U				
T				

Table 12: Parameter values resulting from fragility function construction using population exposure. Parameters for Damage State 1 are marked with clear cells while parameters for Damage State 2 are marked with blue cells. When adjusting for the line-cross in transportation plots, only one dispersion value (Beta) was determined for both damage states.

		Excluding Additional 23 Non-liquefaction-damage Events				Including Additional 23 Non-liquefaction-damage Events			
		No Beta Correction		With Beta Correction		No Beta Correction		With Beta Correction	
	Damage State	Theta	Beta	Theta	Beta	Theta	Beta	Theta	Beta
Buildings	1	63865.67	7.44	63822.38	7.44	88238.35	5.84	88192.23	5.85
	2	894735.97	1.99	904921.85	2.01	885103.31	1.93	898021.79	1.95
Buildings, line cross adjusted	1	32089.88	5.32	32023.11	5.33	49579.71	4.75	49440.89	4.75
	2	35869142.8		36072617.6		21698908.8		21847897.2	
Utilities	1	38217.96	3.19	38017.68	3.2	49309.59	3.06	49120.78	3.07
	2	1534641.59	4.49	1539357.84	4.49	1521322.71	4.21	1527443.57	4.21
Transportation	1	2392.02	7.38	2385.86	7.38	8200.68	5.39	8174.77	5.4
	2	2102322.89	5.52	2408307.58	5.53	2281760.87	5.06	2289225.75	5.07

As seen in the Htot-based fragility functions, the parameter correction is less than 1% in all cases. It can again be interpreted as an unnecessary step. In comparison, including the additional 23 NLD events has a fairly large impact on the parameters. This can be interpreted as again reducing bias towards events with expected liquefaction damage.

The adjustment for crossed lines is preferred again as well. This results in similar choices for preferred fragility functions found using population exposure as those found using Htot, which can be seen in Figure 16.

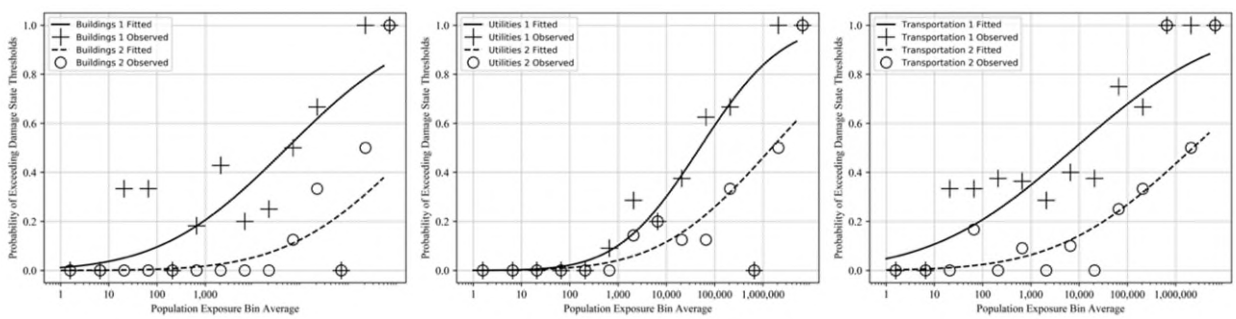


Figure 16: Preferred fragility function results using population exposure, including 23 no-liquefaction damage events, no few-specimen correction, correcting transportation category for lines crossed.

6. Discussion and Next Steps

While creating robust fragility function parameters, one requirement is that the damage level thresholds are clear and not subject to interpretation (Porter, 2020). Another drawback regarding Bird and

Bommer (2004) methodology is that liquefaction damage states are determined in regard to total damage for each event. Specific damage in terms of dollar amounts is not recorded. This leaves damage state classifications up to some subjectivity of future students following their methodology. This interpretation becomes increasingly difficult when considering tertiary hazards such as floods or fires caused by liquefaction.

As mentioned in Bird and Bommer (2004), using reconnaissance reports can be challenging. First, there is “invariably some ambiguity in the reported damage”. This is evident in cases where the extent of damage is not clearly described, and author’s judgement was required to determine if a piece of infrastructure needed to be partially or fully replaced. Second, in some older events, vocabulary surrounding liquefaction and ground failure had not yet been fully developed, so it was necessary to rely upon descriptors such as “pore-pressure induced settlement”. Both of these issues may present more uncertainty when attempting precise damage cost estimates rather than broad damage states.

In Figure 3, it was shown that transportation damages compose a majority of total event damage in most high-excitation measure events. This is important to understand as an increased focus on transportation infrastructure in future work can help explain loss estimates more than building or utility infrastructure. Transportation loss is also not as related to population exposure. There are typically more GIS datasets and proxies for transportation infrastructure than the other categories so an increased focus on transportation infrastructure is possible. Sources such as OpenStreetMap (OSM) provide critical data including road and railroad networks, airport locations, and port locations.

As mentioned in the Results section, preferred fragility functions include the 23 no-liquefaction-damage events and the correction for lines crossing, but do not include the correction for few specimens, shown in Figure 15 and Figure 16.

In on-going work that could not be presented herein due to time constraints, fragility functions will be constructed using damage state thresholds of cost as shown in Table 13. By using cost to define damage state thresholds for each category, probabilities will be calculated for exceeding cost thresholds in each category for different excitation measures. Additionally, we are developing confidence intervals for fragility functions. Parameters for Beta distributions of TLSE and population exposure for each event have been calculated and provided by Kate Allstadt of the USGS (personal communication, 2020).

Table 13: Proposed damage state schema for future fragility function construction.

Damage State (DS)	Value Range (2018 USD)
0	< 100,000
1	>= 100,000
2	>= 1 million
3	>= 10 million
4	>= 100 million

7. Conclusion

In this project, dollar values were estimated for liquefaction damages in 17 historical US events, five of which were found not to have any liquefaction damage. In addition to 17 events with observed liquefaction, the dataset includes 23 non liquefaction-damage events to prevent bias in loss predictions. Damage states were assigned to each of these events based on descriptors in Bird and Bommer (2004). Loss due to liquefaction was categorized across three infrastructure categories: buildings, utilities, and transportation. Liquefaction exposure was summarized with Htot and Population Exposure. Liquefaction damage costs were found to be less than 1% of total earthquake damage costs for six of 12 events with any reported liquefaction damage. Of those six with more than 1% damage, only two events (2002 Denali and 1964 Alaska) had more than 10% of total event damage attributed to liquefaction. Fragility functions were constructed for three infrastructure categories to evaluate probabilities of exceeding damage state thresholds at varying excitation measures. Fragility functions were improved for some categories where the original functions crossed using the maximum likelihood estimation method as outlined in Porter (2020). In on-going work, fragility functions will be constructed using dollar values as limits on damage states. Constructing fragility functions using estimated costs instead of "minor/moderate" or "major" damage state descriptors will provide less subjective, standardized methods of analysis and ease interpretation of expected liquefaction damage.

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Appendix

DID	EID	Event	Municipality	Locale	Description	Category	Subcategory	Cost	Lat	Lon	Road Level	Site	Fire
1	1	Loma Prieta	San Francisco	Marina District, General	Gas pipeline system replacement	Utilities	Gas	$34,425,000				M	0
2	1	Loma Prieta	San Francisco	Marina District, General	20% of estimated total building damage	Building	Residential	$14,175,000				M	0
3	1	Loma Prieta	San Francisco	Marina Yacht Harbor	Concrete seawall settlement and lateral spreading on Res. property	Building	Residential	$1,200				S	0
4	1	Loma Prieta	San Francisco	San Francisco Yacht Club	Large parking lot crack, needs demolition	Building	Commercial	$41,504				S	0
5	1	Loma Prieta	San Francisco	San Francisco Yacht Club	Masonry wall cracked in several places on Res. property, replace	Building	Residential	$19,596				S	0
6	1	Loma Prieta	San Francisco	San Francisco Yacht Club	Concrete connection between buildings	Building	Commercial	$1,766				S	0
7	1	Loma Prieta	San Francisco	San Francisco Yacht Club	Moderate damage to utilities (estimated 10 pipe breaks)	Utilities	Water	$8,071				S	0
8	1	Loma Prieta	San Francisco	San Francisco Yacht Club	Extensive damage to utilities (estimated 20 pipe breaks)	Utilities	Water	$16,141				S	0
9	1	Loma Prieta	San Francisco	San Francisco Yacht Club	South Wing building demolished and rebuilt	Building	Commercial	$662,105				S	0
10	1	Loma Prieta	San Francisco	Marina District, General	Road damages, estimated as 20% of total road and water damages to area as water damages discussed much more frequently	Transportation	Road	$1,146,310			3	M	0
11	1	Loma Prieta	San Francisco	Marina District, General	2.7 km of water mains replaced. Cost estimated as 20% of total road and water damages to area as water damages discussed much more frequently	Utilities	Water	$4,585,239				M	0
12	1	Loma Prieta	San Francisco	Mission District & South of Market, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total settlement damages for this area	Utilities	Gas	$3,543,637				M	0
13	1	Loma Prieta	San Francisco	Mission District & South of Market, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total settlement damages for this area	Building	Residential	$306,781				M	0
14	1	Loma Prieta	San Francisco	Mission District & South of Market, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total settlement damages for this area	Building	Industrial	$306,781				M	0
15	1	Loma Prieta	San Francisco	Mission District &	Estimated liquefaction-induced settlement damages	Building	Commercial	$920,343				M	0

				South of Market, general	based on percent damage to each category of Marina District and total settlement damages for this area								
16	1	Loma Prieta	San Francisco	Mission District & South of Market, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total settlement damages for this area	Utilities	Water	$474,466				M	0
17	1	Loma Prieta	San Francisco	Mission District & South of Market, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total settlement damages for this area	Transportation	Road	$117,993			3	M	0
18	1	Loma Prieta	San Francisco	Port of San Francisco	Settlement damage	Transportation	Port	$7,290,000				M	0
19	1	Loma Prieta	San Francisco	Treasure Island and Hunter's point	Damage to collector roads in middle part of island, where liquefaction without lateral spread occurred (settlement)	Transportation	Road	$850,500			3	M	0
20	1	Loma Prieta	San Francisco	Treasure Island and Hunter's point	44 pipeline breaks, other utilities damage, many due to liquefaction	Utilities	Water	$7,654,500				M	0
21	1	Loma Prieta	Oakland	Bay Bridge Toll Plaza	Lateral spreading to road class 4	Transportation	Road	$1,012,500			4	S	0
22	1	Loma Prieta	Oakland	Bay Bridge Toll Plaza	Lateral spreading to structures comprising toll plaza	Building	Public	$4,050,000				S	0
23	1	Loma Prieta	Alameda	Naval Air Station	Lateral spreading to runways	Transportation	Airport	$2,227,500				M	0
24	1	Loma Prieta	Alameda	Naval Air Station	Lateral spreading to buildings	Transportation	Airport	$2,227,500				S	0
25	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Utilities	Gas	$3,543,637				M	0
26	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Building	Residential	$306,781				M	0
27	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Building	Industrial	$306,781				M	0

28	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Building	Commercial	$920,343				M	0
29	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Utilities	Water	$474,466				M	0
30	1	Loma Prieta	Alameda	Alameda, general	Estimated liquefaction-induced settlement damages based on percent damage to each category of Marina District and total lateral spreading damages for this area	Transportation	Road	$117,993			3	M	0
31	1	Loma Prieta	Monterey Bay	Moss Landing Laboratory	Lateral spreading destroyed lab buildings	Building	Insitutional	$16,200,000	36.794	-121.788		S	0
32	1	Loma Prieta	Watsonville	0.4 km south of Main St, Watsonville	Short railroad bridge deformed by lateral spread	Transportation	Rail_Bridge	$1,609,870				S	0
33	1	Loma Prieta	Monterey Bay	Moss Landing road approach	Moss Landing road approach settlement (class 2)	Transportation	Road	$20,981	36.795	-121.786	2	S	0
34	1	Loma Prieta	Marina District	Marina District, General	FIRE damage to public and private property (assume almost entirely Res. in Marina District)	Building	Residential	$4,050,000				M	1
35	1	Loma Prieta	Monterey Bay	PG&E power plant near Moss Landing	Several water tanks damaged, one ruptured	Utilities	Water	$1,220,112				M	0
36	1	Loma Prieta	Oakland	Oakland Airport	1/3 of runway and adjacent taxiway damaged by lateral spread	Transportation	Airport	$62,775,000				M	0
37	1	Loma Prieta	Oakland	Oakland Port	Subsidence of water utilities	Utilities	Water	$13,162,500				M	0
38	1	Loma Prieta	Neponset	Salinas River near Neponset	Southern Pacific Railroad bridge deformed by lateral spread	Transportation	Rail_Bridge	$1,609,870				S	0
39	1	Loma Prieta	Oakland	Oakland Port	Seventh Street Marine Terminal settlement	Transportation	Port	$103,275,000				M	0
40	1	Loma Prieta	Oakland	Oakland Port	Subsidence of wharves	Transportation	Port	$26,325,000				M	0
41	1	Loma Prieta	Oakland	Oakland Port	Subsidence of gas utilities	Utilities	Gas	$13,162,500				M	0
42	1	Loma Prieta	Pajaro, general, and San Lorenzo, general	Pajaro River Levees and San Lorenzo River Levees	4200 ft of levee repair on each river, unequal costs because made of different material/heights	Utilities	Water	$7,290,000				M	0
43	1	Loma Prieta	Santa Cruz	Santa Cruz, general	18 pipe breaks	Utilities	Water	$24,479				M	0
44	1	Loma Prieta	Santa Cruz	Santa Cruz, general	49 sidewalk pavement damages	Transportation	Road	$15,876			1	M	0
45	1	Loma Prieta	Santa Cruz	Santa Cruz, general	23 residences, estimated average 40% replacement	Building	Residential	$304,917				M	0

					value needed, "most damage due to shaking" so estimate 5% due to liquefaction (Holzer estimated 20% when high liquefaction expected)								
46	1	Loma Prieta	Santa Cruz	Santa Cruz, general	30 residences demolished and full replacement value needed, "most damage due to shaking" so estimate 5% due to liquefaction (Holzer estimated 20% when high liquefaction expected)	Building	Residential	$994,294				M	0
47	2	Northridge	Granada Hills	Balboa Boulevard	Soil erosion from broken water mains formed large craters in some streets	Transportation	Road	$395,861			4	M	0
48	2	Northridge	Granada Hills	Balboa Boulevard	Several broken water mains (estimate roughly five)	Utilities	Water	$6,862				M	0
49	2	Northridge	Granada Hills	Balboa Boulevard	Several broken gas lines (estimate roughly five)	Utilities	Gas	$6,862				M	0
50	2	Northridge	Granada Hills	Granada Hills, general	Widespread roadway cracking	Transportation	Road	$3,441			3	M	0
51	2	Northridge	Simi Valley	Richardson Highway	47 pipe breaks in area of high liquefaction susceptibility, assign 20% of pipe breakge to liquefaction	Utilities	Water	$12,901				M	0
52	2	Northridge	Simi Valley	Rory Lane, Simi Valley	Rory Lane cracking	Transportation	Road	$3,584	34.2697	-118.674		S	0
53	2	Northridge	Simi Valley	Christine Avenue, Simi Valley	Christine Avenue cracking	Transportation	Road	$7,941	34.2684	-118.6697		S	0
54	2	Northridge	Simi Valley	Kuehner Drive, Simi Valley	Kuehner Drive pavement buckling	Transportation	Road	$1,324				S	0
55	2	Northridge	Simi Valley	Christina Avenue, Simi Valley	Masonry wall damage near Christine Avenue	Building	Residential	$833	34.2684	-118.6696		S	0
56	2	Northridge	San Fernando Valley	San Fernando Valley, general	1600 Water pipe breaks, attribute 60% to liquefaction	Utilities	Water	$1,317,550				M	0
57	2	Northridge	San Fernando Valley	San Fernando Power Plant	Soil to repair 15-foot tall lake embankment	Utilities	Water	$33,831	34.312	-118.492		S	0
58	2	Northridge	San Fernando Valley	San Fernando Power Plant	Asphalt to repair 15-foot tall lake embankment	Utilities	Water	$15,293	34.312	-118.492		S	0
59	2	Northridge	San Fernando Valley	San Fernando Power Plant	Foundation pier movements for above-ground water conduit	Utilities	Water	$1,372	34.312	-118.492		S	0
60	2	Northridge	Los Angeles	Upper Van Norman Lake	~50 meters of rails need replacement	Transportation	Rail	$137,245	34.306	-118.493		S	0
61	2	Northridge	San Fernando Valley	San Fernando Valley, general	Gas pipe breaks	Utilities	Gas	$5,490				M	0
62	2	Northridge	Santa Clara	Santa Clara, general	Water pipe breakage	Utilities	Water	$47,531				M	0
63	2	Northridge	Santa Clarita	Santa Clarita, general	Pavement distress, estimated 100 sq ft replacement	Transportation	Road	$956			2	M	0
64	2	Northridge	Santa Clarita	Santa Clarita, general	Significant pipe breakage, estimated 10 pipes broken	Utilities	Water	$13,725				M	0

65	2	Northridge	Santa Clarita	Santa Clarita, general	Oil ruptures, at least 3 of 4 due to liquefaction	Transportation	Gas	$4,117				M	0
66	2	Northridge	Santa Clarita	Santa Clarita, general	Water storage tank collapse	Utilities	Water	$1,464,134				S	0
67	2	Northridge	Los Angeles	Marina Del Ray	"Some pipe breakage", estimate five pipes broken	Utilities	Water	$6,451				M	0
68	2	Northridge	Redondo Beach	King Harbor Mole B	"Almost every pipe behind the failed wall broke": Estimated five water pipe breaks	Utilities	Water	$6,451	33.848	-118.399		S	0
69	2	Northridge	Redondo Beach	King Harbor Mole B	"Almost every pipe behind the failed wall broke": Estimated one gas pipe break	Utilities	Gas	$1,290	33.848	-118.399		S	0
70	2	Northridge	Los Angeles	Joseph Jensen Filtration Plant	85-inch diameter pipe burst (estimate cost equivalent to five typical pipe breaks)	Utilities	Water	$6,451	34.315	-118.497		S	0
71	2	Northridge	Redondo Beach	King Harbor Mole B, Yacht Club	2 buildings distorted from settlemnt	Building	Commercial	$150,319	33.85	-118.396		S	0
72	2	Northridge	Los Angeles	Joseph Jensen Filtration Plant	Parking lot pavement cracking	Utilities	Water	$423,533	34.315	-118.497		S	0
73	2	Northridge	Redondo Beach		Seaside Lagoon	Building	Commercial	$5,083,800	33.845	-118.395		S	0
74	2	Northridge	Redondo Beach	King Harbor Mole B	King Harbor Mole B Parking ruined	Transportation	Port	$397,062	33.85	-118.397		S	0
75	2	Northridge	Redondo Beach	King Harbor Mole B	Many automobiles damages, estimate 2018 costs of 10 cars sustaining $5,000 of damage each	Transportation	Port	$50,000	33.85	-118.397		S	0
76	2	Northridge	Los Angeles	Port of LA	Port of LA dock, cranes, power, ground cracking	Transportation	Port	$84,730	33.737	-118.265		S	0
77	2	Northridge	Santa Monica	Santa Monica, general	Santa Monica earthquake-related fires, assume only 50% due to liquefaction related fires, fire department estimate so addition of contents value not needed	Building	Residential	$711,640				M	1
78	2	Northridge	Santa Monica	Santa Monica, general	Santa Monica earthquake-related fires, assume only 50% due to liquefaction related fires, fire department estimate so addition of contents value not needed	Building	Commercial	$304,988				M	1
79	2	Northridge	Los Angeles	Pacoima and Granada Hills, general	Pacoima and Granada Hills earthquake-related fires, assume only 50% due to liquefaction related fires, LAFD estimate so addition of contents value not needed	Building	Residential	$7,349,703				M	1
80	2	Northridge	Los Angeles	Pacoima and Granada Hills, general	Pacoima and Granada Hills earthquake-related fires, assume only 50% due to liquefaction related fires, LAFD estimate so addition of contents value not needed	Building	Commercial	$3,149,873				M	1

81	4	Napa	Edgerley Island	Edgerley Island, Milton Road	Milton Road ground cracking, estimate 15x15 ft need replacement	Transportation	Road	$2,131	38.198	-122.316	3	S	0
82	4	Napa	Edgerley Island	Edgerley Island, general	Docks and floodwall damaged at one residence	Building	Residential	$1,360				S	0
83	4	Napa	Green Island	Green Island Salt Pond Retaining Dike	Soil Cracking and settling, needs some replacement	Utilities	Water	$2,939	38.2	-122.3		S	0
84	5	Baja	Francisco Morgula	San Felipito Bridge	Train bridges destroyed, needs replacement	Transportation	Rail_Bridge	$8,471,900	32.244	-115.053		S	0
85	5	Baja	Francisco Morgula	San Felipito Bridge	Road bridges destroyed, needs replacement	Transportation	Road_Bridge	$677,752	32.244	-115.053		S	0
86	5	Baja	Tijuana, Baja California	UABC	4 Identical 4-story steel braced frame structures	Building	Insitutional	$5,737,620	32.533	-116.964	4	S	0
87	5	Baja	Tijuana, Baja California	UABC	3 story structure	Building	Insitutional	$1,200,674	32.533	-116.964	3	S	0
88	5	Baja	Tijuana, Baja California	UABC	Parking lot half demolished at university	Building	Insitutional	$245,100	32.533	-116.964		S	0
89	5	Baja	Tijuana, Baja California	UABC	Concrete culvert for water collapse	Utilities	Water	$5,388	32.533	-116.964		S	0
90	5	Baja	Tijuana, Baja California	UABC	Baja California Secretary of Public Safety Building floor slab rotated, no damage to structure or floor slab	Building	Insitutional	$630,643				S	0
91	5	Baja	Tijuana, Baja California	UABC	Pedestrian footbridge	Transportation	Pedestrian Bridge	$105,899	32.533	-116.964		S	0
92	5	Baja	Tijuana, Baja California	UABC	5 identical 2-story buildings	Building	Insitutional	$527,892	32.533	-116.964	2	S	0
93	5	Baja	Tijuana, Baja California	UABC	2-story high school large cracks down side of building	Building	Insitutional	$927,311	32.533	-116.964	2	S	0
94	5	Baja	Mexicali	Mexicali, general	Vacation units damaged by lateral spreading along Rio Hardy, likely full replacement	Building	Residential	$356,140				S	0
95	5	Baja	Mexicali	Mexicali, general	Residence suffered severe damage from lateral spreading, likely full replacement	Building	Residential	$178,070	32.238	-115.302		S	0
96	5	Baja	Mexicali	Mexicali, general	Interior of farm house damaged by lateral spreading, likely full replacement	Building	Residential	$178,070	32.238	-115.301		S	0
97	5	Baja	Mexicali	Mexicali, general	Two-story structure settledd ~1 meter, likely due to bearing-capacity failure, likely full replacement	Building	Residential	$178,070	32.35	-115.18		S	0
98	5	Baja	Mexicali	Mexicali, general	Many residential structures suffered moderate to severe damage in areas where surface manifestations of liquefaction present	Building	Residential	$1,424,559				M	0
99	5	Baja	El Centro	Drew Road Bridge, north side	Approach damaged to settlement, traffic class 4	Transportation	Road	$34,834	32.762	-115.69	4	S	0

100	5	Baja	El Centro	Drew Road Bridge, south side	Approach damaged to settlement, traffic class 4	Transportation	Road	$20,815	32.761	-115.69	4	S	0
101	5	Baja	Mt Signal	Brockman Road at Greeson Drain	Approaches damaged due to settlement, traffic class 3	Transportation	Road	$8,496			3	S	0
102	5	Baja	El Centro	Lyons Road at New River	Approach deformation, lateral spreading nearby, traffic class 4	Transportation	Road	$41,652	32.717	-115.604	4	S	0
103	5	Baja	El Centro	I-8 Westbound shoulder	Pavement settled differentially	Transportation	Road	$1,498			5	S	0
104	5	Baja	El Centro	Sunbeam Lake, Drew Road	Embankment next to lake settled, damaged adjacent road class 4	Transportation	Road	$86,775	32.784	-115.691	4	S	0
105	5	Baja	El Centro	Sunbeam Lake, Drew Road	Embankment next to lake settled, damaged utility pipe	Utilities	Water	$1,271	32.784	-115.691		S	0
106	5	Baja		Highway 2 bridge	Shear key cracking, expansion joint damage, permanent distortion of bearing pads	Transportation	Road_Bridge	$423,595				S	0
107	5	Baja		Highway 5 bridges	Significant bridge movemet due to liquefaction and lateral spread	Transportation	Road_Bridge	$271,101				S	0
108	5	Baja		Highway 5 bridge approaches	Approach damaged to liquefaction and lateral spread, traffic class 5	Transportation	Road	$57,523			5	S	0
109	5	Baja		Fig Lagoon	Embankment levee had liquefaction-induced slump	Utilities	Water	$3,350				S	0
110	5	Baja	Baja California, general	Baja, California Crop Damages	Wheat subsidence, flooding, & drought due to canal breaks	Utilities	Agriculture	$15,865,678				M	0
111	5	Baja	Baja California, general	Baja, California Crop Damages	Hay subsidence, flooding, & drought due to canal breaks	Utilities	Agriculture	$16,641,730				M	0
112	5	Baja	Baja California, general	Baja, California Canals	Major Canal Damage	Utilities	Water	$1,705,513				M	0
113	5	Baja	Baja California, general	Baja, California Canals	Minor Canal Damage	Utilities	Water	$24,714,875				M	0
114	5	Baja	Baja California, general	Baja, California Canals	Drainage Canal Damage	Utilities	Water	$16,100,042				M	0
115	7	Nisqually	Seattle		Sinkhole broke asphalt and soil of walkway, needs to be filled and paved	Transportation	Road	$2,045	47.586	-122.34	1	S	0
116	7	Nisqually	Seattle	Slightly east of Boeing Field	Parking lot deep cracking, replacement needed	Transportation	Airport	$163,400	47.534	-122.314		S	0
117	7	Nisqually	Seattle	North Deschutes Parkway	Road lateral spreading, collapse, pavement to replace	Transportation	Road	$312,401	47.042	-122.911	4	S	0
118	7	Nisqually	Seattle	North Deschutes Parkway	4th Ave Bridge slightly damaged	Transportation	Bridge	$49,815	47.043	-122.911		S	0
119	7	Nisqually	Seattle	North Deschutes Parkway	Embankment collapse of soil near water	Utilities	Water	$32,830	47.042	-122.912		S	0

120	7	Nisqually	Olympia	Marathon Park	Small bathroom housing structure collapse	Building	Public	$6,568	47.037	-122.912	3	S	0
121	7	Nisqually	Olympia	Marathon Park	Small bathroom water pipes	Utilities	Water	$2,491	47.037	-122.912		S	0
122	7	Nisqually	Olympia	Central West Deschutes Parkway	Large cracks in direction of road	Transportation	Road	$829	47.036	-122.912	1	S	0
123	7	Nisqually	Olympia	Capitol Interpretive Center	Site A soil settled, ~67 cubic yards replaced	Utilities	Soil	$2,200	47.043	-122.911		S	0
124	7	Nisqually	Olympia	Capitol Interpretive Center	Site B soil settled, ~80 cubic yards replaced	Utilities	Soil	$2,626	47.024	-122.905	4	S	0
125	7	Nisqually	Olympia	Capitol Interpretive Center	Site B walkway settled and replaced	Transportation	Road	$622	47.024	-122.905	1	S	0
126	7	Nisqually	Olympia	Capitol Interpretive Center	Site C walkway settled and replaced	Transportation	Road	$4,154	47.024	-122.907	1	S	0
127	7	Nisqually	Olympia	Capitol Interpretive Center	Site C ~420 cubic yards soil replaced after settling	Transportation	Road	$13,789	47.024	-122.907	1	S	0
128	7	Nisqually	Olympia	Capitol Interpretive Center	Site D cement and soil settled, replaced	Transportation	Road	$10,717	47.025	-122.908	1	S	0
129	7	Nisqually	Olympia	Capitol Interpretive Center	Site E, soil and cement need complete replacement	Transportation	Road	$18,446	47.025	-122.91	1	S	0
130	7	Nisqually	Turnwater	Sunset Lake	Cement Demolition and repair	Transportation	Road	$32,157	47.002	-122.924	2	S	0
131	7	Nisqually	Turnwater	Sunset Lake	Gas pipe break	Utilities	Gas	$1,245	47.002	-122.924		S	0
132	7	Nisqually	Seattle	King County International Airport	85 meter long vertical runway crack	Transportation	Airport	$2,633,067	47.528	-122.302		S	0
133	7	Nisqually	Seattle	King County International Airport	35 meter vertical crack between Storm drains	Transportation	Airport	$921,573	47.528	-122.302		S	0
134	7	Nisqually	Harbor Island, Seattle	Water Structures at Terminal 18	13 cm vertical cement drop	Transportation	Port	$3,079	47.576	-122.347		S	0
135	7	Nisqually	Harbor Island, Seattle	Water Structures at Terminal 18	Small water pipe break	Utilities	Water	$1,411	47.576	-122.347		S	0
136	7	Nisqually	Harbor Island, Seattle	Terminal 18	Circular crack with vertical offset	Transportation	Port	$615	47.589	-122.349		S	0
137	7	Nisqually	Harbor Island, Seattle	Terminal 30	300 foot long crack	Transportation	Port	$1,409	47.585	-122.341		S	0
138	7	Nisqually	Seattle	South Downtown, Seattle	Sidewalk settlement	Transportation	Road	$563	47.582	-122.333	1	S	0
139	7	Nisqually	Seattle	South Downtown, Seattle	4-inch water pipe break	Utilities	Water	$1,411	47.582	-122.333		S	0
140	7	Nisqually	Seattle	South Downtown, Seattle	Warehouse basement sand and damage	Building	Industrial	$119,936	47.575	-122.335		S	0

141	7	Nisqually	Seattle	South Downtown, Seattle	Falling apart red masonry building	Building	Commercial	$613,858	47.584	-122.334		S	0
142	7	Nisqually	Seattle	South Downtown, Seattle	Door and cement leading to back of building C	Building	Commercial	$12,277	47.578	-122.334		S	0
143	7	Nisqually	Seattle	South Downtown, Seattle	Two attached Building collapsed, attributing ~10% to liquefaction	Building	Commercial	$2,406,125	47.578	-122.334		S	0
144	7	Nisqually	Seattle	US Naval Reserve Center, next to Building #10	Sidwalk settled a few inches	Transportation	Road	$1,043	47.589	-122.336	1	S	0
145	9	Denali	Northway, Alaska	Northway Airport	Fissures, sand vents, sinkholes on runway	Transportation	Airport	$18,147,610	62.962	-141.927		S	0
146	9	Denali	Tok, Alaska	Tok Cutoff (Highway)	Major lateral spreading, soil needs replacement for ~200 ft for both lanes and shoulders	Transportation	Road	$84,767			4	M	0
147	9	Denali	Tok, Alaska	Tok Cutoff (Highway)	Major lateral spreading damage, 1.7 miles	Transportation	Road	$3,547,595			4	M	0
148	9	Denali	Paxson	Fielding Lake	Outhouse damage	Building	Institutional	$3,386	63.193	-145.65		S	0
149	9	Denali	Paxson	Fielding Lake	First shed damaged	Building	Institutional	$6,772	63.193	-145.65		S	0
150	9	Denali	Paxson	Fielding Lake	Second shed damaged	Building	Institutional	$3,386	63.193	-145.65		S	0
151	9	Denali	Mentasta Lake	Mabel Creek Bridge	Bridge Type HWB17 Replaced	Transportation	Road_Bridge	$2,067,412	62.863	-143.672		S	0
152	9	Denali	Mentasta Lake	Slana Slough Bridge	Bridge Type HWB17 Replaced	Transportation	Road_Bridge	$2,067,412	62.859	-143.685		S	0
153	10	San Simeon	Oceano	Oceano, general	Water pipe damage	Utilities	Water	$7,253				M	0
154	10	San Simeon	Arroyo Grande Creek	Liquefaction and related settlement of levee	Utilities	Water	$173,571					M	0
155	10	San Simeon	Templeton	Templeton Road Bridge	Bridge APPROACH settled 13 cm, needs 28 sq ft of asphalt ramp, traffic class 3	Transportation	Road	$770	35.543	-120.708	3	S	0
156	10	San Simeon	Templeton	Templeton Road Bridge Utilities Lines	Utilities lines damaged	Utilities	Gas	$2,719	35.543	-120.708		S	0
157	10	San Simeon	Templeton	Templeton Road Bridge Utilities Lines	Utilities lines damaged	Utilities	Water	$2,719	35.543	-120.708		S	0
158	10	San Simeon	Oceano	Oceano Airport	Runway damage	Transportation	Airport	$880,664	35.102	-120.623	3	S	0
159	10	San Simeon	Oceano	Oceano, general	House foundation offset, house appears demolished on real estate website	Building	Residential	$274,931	35.109	-120.623		S	0
160	11	Anchorage	Anchorage	Alaskan Native Tribal Health Consortium	3900 Ambassador Drive, damage to entryway	Building	Commercial	$2,226,740	61.1821	-149.8066		S	0
161	11	Anchorage	Anchorage	Alaskan Native Tribal Health Consortium	4000 ambasador Drive, brick deck structure settlement	Building	Commercial	$5,566,849	61.1828	-149.8061		S	0
162	11	Anchorage	Anchorage	Alaska Department of Fish and Game	Building settled up to 1 ft	Building	Commercial	$1,837,326	61.1593	-149.88879		S	0

163	11	Anchorage	Anchorage	Jamestown Drive	Series of condominiums settled up to 1 ft	Building	Residential	$574,380	61.12951	-149.84587		S	0
164	11	Anchorage	Anchorage	Jamestown Drive	Concrete driveways cracked up to 7 cm on property	Building	Residential	$3,949	61.12951	-149.84587		S	0
165	11	Anchorage	Anchorage	Anchorage, general	50 water pipe breaks according to Anchorage Water and Wastewater Utility, attribute 20% due to liquefaction	Utilities	Water	$16,139				M	0
166	11	Anchorage	Eagle River	Ptarmigan Drive	Walkway settlement of 5 inches on property	Building	Residential	$1,096	61.307	-149.506		S	0
167	11	Anchorage	Anchorage	Arlene Drive	Settlement and damage to driveway	Building	Residential	$1,990	61.13337	-149.93126		S	0
168	11	Anchorage	Anchorage	Arlene Drive	Settlement and minor damage to house	Building	Residential	$31,784	61.13337	-149.93126		S	0
169	11	Anchorage	Anchorage	Ticia Circle	Settlement and damage to nearly all duplexes, 9 on street, assume moderate damage to one and light damage to others	Building	Residential	$429,151	61.13794	-149.938		S	0
170	11	Anchorage	Anchorage	Dowling Street	Settlement at intersection of Dowling Street and C street	Transportation	Road	$2,281	61.166621	-149.886609	1	S	0
171	11	Anchorage	Anchorage	Dowling Street	Settlement at intersection of Dowling Street and C street	Transportation	Road	$3,372	61.166621	-149.886609	4	S	0
172	11	Anchorage	Anchorage	Minnesota Boulevard	Highway onramp failure due to lateral spreading and slumping	Transportation	Road	$38,049	61.171279	-149.915546	5	S	0
173	11	Anchorage	Anchorage	Minnesota Boulevard	Additional cracking of roadway on highway side of off ramp	Transportation	Road	$22,830	61.171279	-149.915546	5	S	0
174	11	Anchorage	Anchorage	Minnesota Boulevard	Highway onramp failure due to lateral spreading and slumping	Transportation	Road	$25,212	61.171279	-149.915546	5	S	0
175	11	Anchorage	Anchorage	Anchorage, general	More than 300 natural gas leaks reported across Anchorage according to EERI report. Arbitrarily assume 20% of breaks due to liquefaction damage (60 breaks)	Utilities	Gas	$96,389				M	0
176	12	1964 Alaska	Cordova	Cordova Airport	Runway aprons sustained moderate ground cracking	Transportation	Airport	$423,595	60.543643	-145.725615		S	0
177	12	1964 Alaska	Cordova	Cordova Airport	Office building concrete slab cracked , 5% value repair	Transportation	Airport	$510,593	60.543643	-145.725615		S	0
178	12	1964 Alaska	Cordova	Cordova Airport	Cordova control tower concrete slab cracked, 5% value repair	Transportation	Airport	$510,593	60.544	-145.725			0
179	12	1964 Alaska	Cordova	Cordova Airport	Underground water and stream lines broken, need replace	Utilities	Water	$65,000	60.544	-145.725			0
180	12	1964 Alaska	Kodiak	Kodiak Naval Station	Main runways damaged and asphalt taxiways cracked	Transportation	Airport	$2,004,600	57.751582	-152.495405			0
181	12	1964 Alaska	Kodiak	Kodiak Naval Station	Hangar settled at one corner	Transportation	Airport	$20,000	57.751582	-152.495405			0
182	12	1964 Alaska	Kenai	Kenai Muni Airport	airstrips damage, partially due to surficial settlement	Transportation	Airport	$1,649,400	60.570471	-151.249769			0

183	12	1964 Alaska	Whittier	Whittier airport	Gravel airstrip severly damaged due to fill failure	Transportation	Airport	$600,000	60.778458	-148.715969			0
184	12	1964 Alaska	Whittier	Whittier port	Extensive damage to dock and port facilites attributed to many factors	Transportation	Port	$931,709	60.778327	-148.696895			0
185	12	1964 Alaska	Seward	Homer Spit Port	All port facilities destroyed and rebuilt elsewhere due to unstable soils	Transportation	Port	$4,658,546	60.121539	-149.424758			0
186	12	1964 Alaska	Valdez	Valdez port	All port facilites destroyed due to submarine slide, settlement	Transportation	Port	$24,300,000	61.124615	-146.337197			0
187	12	1964 Alaska	Anchorage	Turnagain Arm	Transmission line between Girdwood and Portage severely damaged, 13 towers destroyed	Utilities	Electric	$12,684,000					0
188	12	1964 Alaska	Anchorage	Anchorage, general	Ground fractures and liquefaction-induced landslides broke pipes in 100 places	Utilities	Water	$77,518				M	0
189	12	1964 Alaska	Valdez	Richardson Highway	Richardson Highway damaged from mile 0.0 to 5.0	Transportation	Road	$9,773,285			5		0
190	12	1964 Alaska	Portage	Seward-Anchorage Highway	Damage to 14.9 mile section (75.1 to 90)	Transportation	Road	$31,695,071			5		0
191	12	1964 Alaska	Anchorage	Seward-Anchorage Highway	Fractures due to liquefaction (99 to 105)	Transportation	Road	$6,381,558			5		0
192	12	1964 Alaska	Primrose	Seward-Anchorage Highway	extensive damage at snow river crossing, piers subsided, roadway subsided up to 11 ft	Transportation	Road	$1,208,628	60.333944	-149.350299	5		0
193	12	1964 Alaska	Cordova	Copper River Highway	Fill subsided 3 feet around mile 27.1	Transportation	Road	$732,496	60.444826	-145.065422	5		0
194	12	1964 Alaska	Cordova	Copper River Highway	Damage for 5.1 miles due to local subsidence and lateral displacement	Transportation	Road	$3,735,729			5		0
195	12	1964 Alaska	Cooper Landing	Sterling Highway	Damage due to soil failure around mile 71, highway moved up to 4 feet	Transportation	Road	$3,115,213	60.470322	-150.398454	5		0
196	12	1964 Alaska	Cooper Landing	Sterling Highway	Damage due to soil failure around mile 75, highway moved up to 4 feet	Transportation	Road	$4,153,618	60.498787	-150.483715	5		0
197	12	1964 Alaska	Chiniak	Chiniak Highway	4 mile stretch of Chiniak Highway on Kodiak Island failed	Transportation	Road	$546,315			5		0
198	12	1964 Alaska	Alaska, general	Alaska, general	All road bridges damaged by liquefaction according to spreadsheet	Transportation	Road Bridge	$167,642,288					0
199	12	1964 Alaska	Seward	Seward, general	Alaska Railroad Bridge 3.0 damaged due to settlement	Transportation	Rail_Bridge	$92,486	60.138124	-149.421707		S	0
200	12	1964 Alaska	Seward	Seward, general	Alaska Railroad Bridge 3.2 damaged due to settlement	Transportation	Rail_Bridge	$91,395	60.140075	-149.419327		S	0
201	12	1964 Alaska	Seward	Seward, general	Alaska Railroad Bridge 3.3 damaged due to settlement	Transportation	Rail_Bridge	$102,641	60.141502	-149.4179		S	0
202	12	1964 Alaska	Bear Creek	Bear Creek, general	Alaska Railroad Bridge 14.5 damaged due to settlement	Transportation	Rail_Bridge	$74,207	60.286507	-149.339606		S	0

203	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 114.3 damaged due to settlement	Transportation	Rail_Bridge	$37,103	61.224068	-149.892751		S	0
204	12	1964 Alaska	Butte	Butte, general	Alaska Railroad Bridge 146.4 damaged due to settlement	Transportation	Rail_Bridge	$74,207	61.480921	-149.24369		S	0
205	12	1964 Alaska	Butte	Butte, general	Alaska Railroad Bridge 147.1 damaged due to settlement	Transportation	Rail_Bridge	$74,207	61.491628	-149.240865		S	0
206	12	1964 Alaska	Butte	Butte, general	Alaska Railroad Bridge 147.4 damaged due to settlement	Transportation	Rail_Bridge	$74,207	61.4949	-149.239526		S	0
207	12	1964 Alaska	Butte	Butte, general	Alaska Railroad Bridge 147.5 damaged due to settlement	Transportation	Rail_Bridge	$74,207	61.496982	-149.238783		S	0
208	12	1964 Alaska	Butte	Butte, general	Alaska Railroad Bridge 148.3 damaged due to settlement	Transportation	Rail_Bridge	$74,207	61.506798	-149.239675		S	0
209	12	1964 Alaska	Bear Creek	Bear Creek, general	Alaska Railroad Bridge 4.8 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$71,085	60.162186	-149.403159		S	0
210	12	1964 Alaska	Bear Creek	Bear Creek, general	Alaska Railroad Bridge 6.0 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$111,705	60.178319	-149.394938		S	0
211	12	1964 Alaska	Bear Creek	Bear Creek, general	Alaska Railroad Bridge 15.2 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$9,478	60.29477	-149.331836		S	0
212	12	1964 Alaska	Bear Creek	Bear Creek, general	Alaska Railroad Bridge 15.6 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$30,465	60.301541	-149.331177		S	0
213	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 33.6 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$47,390	60.53831	-149.324346		S	0
214	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 34.5 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$71,085	60.543587	-149.300827		S	0
215	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 34.8 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$71,085	60.545547	-149.292535		S	0
216	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 35.6 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$71,085	60.55007	-149.269167		S	0
217	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 37.0 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$294,495	60.555799	-149.229667		S	0
218	12	1964 Alaska	Moose Pass	Moose Pass, general	Alaska Railroad Bridge 37.3 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$50,775	60.556703	-149.221526		S	0
219	12	1964 Alaska	Portage	Portage, general	Alaska Railroad Bridge 41.6 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$47,390	60.576906	-149.111319		S	0
220	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 58.7 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$121,860	60.761135	-148.994304		S	0
221	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 59.9 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$121,860	60.778162	-148.984387		S	0

222	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 61.1 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$40,620	60.794052	-148.97595		S	0
223	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 61.5 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$10,155	60.800582	-148.972229		S	0
224	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 61.9 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$71,085	60.804988	-148.970163		S	0
225	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 62.1 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$30,465	60.807809	-148.97068		S	0
226	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 62.3 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$30,465	60.810937	-148.971591		S	0
227	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 63.0 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$132,015	60.821026	-148.97497		S	0
228	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 63.5 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$101,550	60.827022	-148.977016		S	0
229	12	1964 Alaska	Anchorage	Anchorage, general	Alaska Railroad Bridge 63.6 damaged due to horizontal landspreading	Transportation	Rail_Bridge	$150,075	60.827022	-148.977016		S	0
230	12	1964 Alaska	Anchorage	Potter	Landsliding due to liquefaction, damaged embankment and tracks	Transportation	Rail	$7,713,889	61.088046	-149.842128		S	0
231	12	1964 Alaska	Primrose	Rocky Creek Delta	Slumping carried away 261 feet of embankment	Transportation	Rail	$466,305	60.377396	-149.354821		S	0
232	12	1964 Alaska	Seward	Seward, general	Embankment damage due to liquefaction between Seward and Portage	Transportation	Rail	$5,920,863				S	0
233	12	1964 Alaska	Whittier	Whittier, general	Embankment damage due to liquefaction between Whittier and Portage	Transportation	Rail	$2,347,897				S	0
234	12	1964 Alaska	Whittier	Whittier, general	Embankment damage due to liquefaction in Whittier	Transportation	Rail	$145,355				S	0
235	12	1964 Alaska	Portage	Portage, general	Embankment damage due to liquefaction between Portage and Anchorage	Transportation	Rail	$3,270,405				S	0
236	12	1964 Alaska	Anchorage	Anchorage, general	Embankment damage due to liquefaction between Anchorage and Matanuska	Transportation	Rail	$2,149,460				S	0
237	12	1964 Alaska	Matanuska	Matanuska, general	Embankment damage due to liquefaction between Matanuska and Fairbanks	Transportation	Rail	$187,028				S	0
238	12	1964 Alaska	Seward	Seward, general	F 5.7	Transportation	Rail_Bridge	$44,230				S	0
239	12	1964 Alaska	Seward	Seward, general	F 9.4	Transportation	Rail_Bridge	$18,956				S	0
240	12	1964 Alaska	Seward	Seward, general	F10.7	Transportation	Rail_Bridge	$18,956				S	0
241	12	1964 Alaska	Whittier	Whittier port	Six lanes for 2400 ft of railway Marshaling destruction	Transportation	Rail	$11,150,000				S	0
242	12	1964 Alaska	Rabbit Creek	Rabbit Creek, general	102.5 bridge	Transportation	Rail_Bridge	$14,841				S	0

243	12	1964 Alaska	Alaska, general	Alaska, general	2 culverts for bridges	Transportation	Rail_Bridge	$13,438				S	0
244	12	1964 Alaska	Anchorage	Anchorage, general	112.8 Bridge, only wood trestles damaged	Transportation	Rail_Bridge	$15,165				S	0
245	12	1964 Alaska	Butte	Butte, general	142.9 Bridge	Transportation	Rail_Bridge	$75,824				S	0
246	12	1964 Alaska	Butte	Butte, general	152.1 Bridge, damage only slight, assume 10% replacement value	Transportation	Rail_Bridge	$3,791				S	0
247	12	1964 Alaska	Butte	Butte, general	152.3 Bridge, damage only slight, assume 10% replacement value	Transportation	Rail_Bridge	$3,791				S	0
248	12	1964 Alaska	Alaska, general	Alaska, general	266.7 Bridge, only reset likely needed, assume 10% replacement value	Transportation	Rail_Bridge	$7,421				S	0
249	12	1964 Alaska	Alaska, general	Alaska, general	284.2 Bridge, only reset likely needed, assume 10% replacement value	Transportation	Rail_Bridge	$7,421				S	0
250	13	Pawnee	Pawnee County		Porch of a residency settles 4 centimeters	Building	Residential	$4,935	36.395	-96.909		S	0
251	18	Puget Sound	Port Orchard, WA	Thriftway Supermarket (closed in 2019)	Northeastern corner of Grocery store parking lot damaged, vertical displacement up to 2 feet (a quarter of lot is 12,500 sq ft)	Building	Commercial	$102,125	47.534	-122.595		S	0
252	18	Puget Sound	Port Orchard, WA	Country Club Road	Road slumped damaging 50-100 ft of pavement	Transportation	Road	$15,930	47.501	-122.596	4	S	0
253	18	Puget Sound	Renton, WA	Boeing Renton Factory	Floors settled away from foundation piling, interior concrete blocks crack, light fixtures fell, ceiling tiles fell	Transportation	Airport	$3,188,660	47.498	-122.208		S	0
254	18	Puget Sound	Seattle	Boeing Field Buildings	Floors settled away from foundation piling, interior concrete blocks crack, light fixtures fell, ceiling tiles fell	Transportation	Airport	$3,539,413	47.528	-122.297		S	0
255	18	Puget Sound			Settling and basement cracking of 2 houses	Building	Residential	$3,006				S	0
256	18	Puget Sound			Road shoulders cracking from slumping	Transportation	Road	$514			4	S	0
257	18	Puget Sound	West Seattle	Alki Point	Water and sand ejection damaged basement	Building	Residential	$6,012	47.576	-122.42		S	0
258	18	Puget Sound	West Seattle	Alki Point	A third of promenade behind seawall sinks 6 inches	Transportation	Road	$13,878	47.576	-122.42	1	S	0
259	18	Puget Sound	West Seattle	Alki Point	Concrete bulkhead (~200 sq ft) twisted and dropped due to soil settling	Transportation	Port	$2,087	47.576	-122.42		S	0
260	18	Puget Sound	Seattle	Pier 5 (renamed as pier 57) & Pier 6	Bulkhead out of line, 10,500 sq ft of concrete needed to replace lost space	Transportation	Port	$2,497,500	47.606	-122.31		S	0
261	18	Puget Sound	Seattle	Fisher Flouring Mills , Harbor Island	Approximately 5 pipe breaks	Utilities	Water	$7,053	47.575	-122.357		S	0
262	18	Puget Sound	Seattle	Piers 15 and 16	Piers shifted towards water by a foot	Transportation	Port	$2,497,500	47.587	-122.353		S	0
263	18	Puget Sound	Seattle	Todd Shipyard Corporation	3 breaks in underground mains	Utilities	Water	$4,232	47.574	-122.356		S	0

264	18	Puget Sound	Seattle	Millwork Supply basement	Basement floor slabs cracked and displaced from 8 inches of settlement, need cement replacement	Building	Commercial	$457,544	47.583	-122.335		S	0
265	18	Puget Sound		House basement concrete floor	Concrete floor cracked and heaved, foundation cracked	Building	Residential	$25,002	47.586	-122.308		S	0
266	18	Puget Sound			Ground cracks in sidewalk north of Union Bay	Transportation	Road	$983			1	S	0
267	18	Puget Sound	Green Lake	South of Green Lake	Ground cracks foundation of small building, fractured walls	Building	Institutional	$46,601	47.671	-122.339		S	0
268	18	Puget Sound	Green Lake	South of Green Lake	Walkways and pavement fractured	Transportation	Road	$983	47.671	-122.339	1	S	0
269	18	Puget Sound	Green Lake	South of Green Lake	Approx 2 utility lines broken	Utilities	Water	$4,232	47.671	-122.339		S	0
270	18	Puget Sound	Green Lake	South of Green Lake	Buckled asphalt blacktop around Aqua Theater	Transportation	Road	$955	47.671	-122.339	1	S	0
271	18	Puget Sound	Green Lake	South of Green Lake	4 inch water main ruptured (normal)	Utilities	Water	$1,411	47.671	-122.339		S	0
272	18	Puget Sound	Kingston, Washington	Highway 104 Three miles west of Kingston	30 ft of highway 104 slumped three feet (~360 sq ft)	Transportation	Road	$5,986	47.806	-122.514	5	S	0
273	18	Puget Sound		Deschutes Parkway, Capitol Lake	250 ft of one lane destroyed, half mile total damaged	Transportation	Road	$718,414	47.025	-122.91	4	M	0
274	18	Puget Sound	Puyallup, Washington	Puyallup High School	Many sand boils, high school's long jump pit needed to be moved	Building	Institutional	$16,548	47.191	-122.302		S	0
275	18	Puget Sound	Tacoma, Washington	Thorne Road	Ground crack along Thorne Rd in port industrial area	Transportation	Road	$14,162	47.262	-122.406	4	S	0
276	18	Puget Sound	Allyn, Washington	Rocky Point	100 ft of highway settles six inches, unstable and needs replacement	Transportation	Road	$39,952	47.369	-122.841	5	S	0
277	18	Puget Sound	Gig Harbor, Washington	Purdy Road near intersection with Crescent Lake Road	Fissure 4 ft deep, approx 3x3 ft at surface need replacement	Transportation	Road	$7,190	47.389	-122.574	5	S	0
278	18	Puget Sound	Gig Harbor, Washington	Road next to park on north side of town	Slump causes 20 ft of road to settle and slide into lake	Transportation	Road	$2,777			4	S	0
279	18	Puget Sound	Vashon Island	Reddings Beach of Vashon Island	1 inch crack 200 ft long through road	Transportation	Road	$885			3	S	0
280	18	Puget Sound	Vashon Island	Klahanie Beach on Vashon Island	Cement deck behind cottage buckled, needs replacement, assumed ~200 sq ft	Building	Residential	$1,521				S	0
281	18	Puget Sound	Vashon Island	Klahanie Beach on Vashon Island	Cottage pushed forward several inches, assume 0.4 damage ratio	Building	Residential	$48,708				S	0
282	18	Puget Sound			Swimming pool and cement patio	Utilities	Water	$4,564				S	0
283	18	Puget Sound		South end of Maury Island	Ground crack 3 inches wide, 100 yards long in road	Transportation	Road	$1,226	47.349	-122.46	2	S	0

284	18	Puget Sound	Kent, Washington	Slightly west of green river	Water main break	Utilities	Water	$1,271	47.378	-122.272		S	0
285	18	Puget Sound	Kent, Washington	Slightly west of green river	Road shoulder collapsed	Transportation	Road	$17,976	47.378	-122.272	2	S	0
286	18	Puget Sound	Renton, WA	Burnett & Seventh street	~1,000 meters of road destroyed	Transportation	Road	$139,500			4	M	0
287	18	Puget Sound	Renton, WA	Shattuck St between South 6th and South 7th St	Foundation crack under a house, house settles 2.5 inches	Building	Residential	$100,108				S	0
288	18	Puget Sound	Renton, WA	Shattuck St between South 6th and South 7th St	Walkway cracks outside house	Building	Residential	$669				S	0
289	18	Puget Sound	Renton, WA	Jones Road	Some brick damage on side of house	Building	Residential	$8,759	47.421	-122.124		S	0
290	18	Puget Sound	Renton, WA	Jones Road	Narrow crack 150 ft long	Transportation	Road	$664	47.421	-122.124	2	S	0
291	18	Puget Sound	Renton, WA	Jones Road	~2 broken water pipes	Utilities	Water	$2,542	47.421	-122.124		S	0
292	18	Puget Sound	Shelton, WA	Highway 101 four miles north of Shelton, WA	One lane slumped for 150 ft	Transportation	Road	$26,964	47.288	-123.173	5	S	0
293	19	Ridgecrest	Trona, CA	Magnolia Ave, Trona	Ground compression in road due to lateral spreading	Transportation	Road	$11,363	35.762	-117.373	3	S	0
294	19	Ridgecrest	Trona, CA	Main St & Magnolia Ave, Trona	Restaurant building's wall cracked	Building	Commercial	$17,421	35.76	-117.376		S	0
295	19	Ridgecrest	Trona, CA		Heavily dmaaged Structure A1 in vicinity of liquefaction	Building	Residential	$67,525	35.746	-117.396		S	0