National Liquefaction Loss Database and Fragility Functions

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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 in earthquakes as observed during the 1964 Alaska event. A geospatial liquefaction model developed by *Zhu et al. 2017* and implemented by the USGS on the ground failure tab of the earthquake overview page is used to estimate liquefaction spatial extent (LSE) after an earthquake. The model estimates LSE using two shaking parameters and four globally available environmental parameters.

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", abbreviated as *Htot*. The USGS Pager system also calculates "aggregate liquefaction population exposure", abbreviated as *PopExp.* However, neither the geospatial liquefaction model nor the USGS Pager system currently predicts infrastructure or economic loss due to liquefaction.

We present a liquefaction loss database of 12 United States events. Each entry in the database is labeled by an infrastructure category: transportation, utilities, and buildings. When possible, liquefaction loss is associated with a spatial location. This database is used to relate economic loss by infrastructure category to *Htot* and *PopExp*. We also present fragility functions for each infrastructure category using the national loss database and damage state thresholds defined by damage costs.

Additionally, we build on work by Bird and Bommer (2004), a global dataset of liquefaction damage states for 50 events, by expanding the dataset to 86 events and developing fragility functions for these damage states. These fragility functions provide probabilities of liquefaction causing minor/moderate damage or major damage relative to the overall event's damage based on one of two excitation measures: *Htot* or *PopExp.*

BUILDING A LIQUEFACTION LOSS DATABASE

- To quantify loss due to liquefaction, we built a database recording damages due to liquefaction in 12 American earthquakes spanning from 1964 to 2019. Damages were recorded based on information presented in government reports, scientific papers, and news articles. The Geotechnical Extreme Events Reconnaissance (GEER) Association provides reports following extreme events which document their impact on the world. These reports were used as primary sources of information.
- GEER reports cover all events in our database, oftentimes mentioning specifically which damages were due to liquefaction. In some cases, damages were mentioned to be caused by "liquefaction-induced settlement", "lateral spread", or "sand boils". These are all examples of liquefaction-induced damages recorded in this database.
- Infrastructure damage costs were estimated primarily using HAZUS-MH 2.1 Technical Manual. Road costs were estimated based on the depth of road necessary for each traffic type, asphalt density of 145 lb/ft^3 and asphalt cost of $100/ton.
- Costs due to liquefaction for all events are in table 1, sorted by ascending Htot values, a measure of estimated liquefaction spatial extent. As seen in the table, liquefaction losses can vary from very little to hundreds of millions of dollars. Thus, properly estimating liquefaction losses can drastically change an earthquake's overall economic impact.

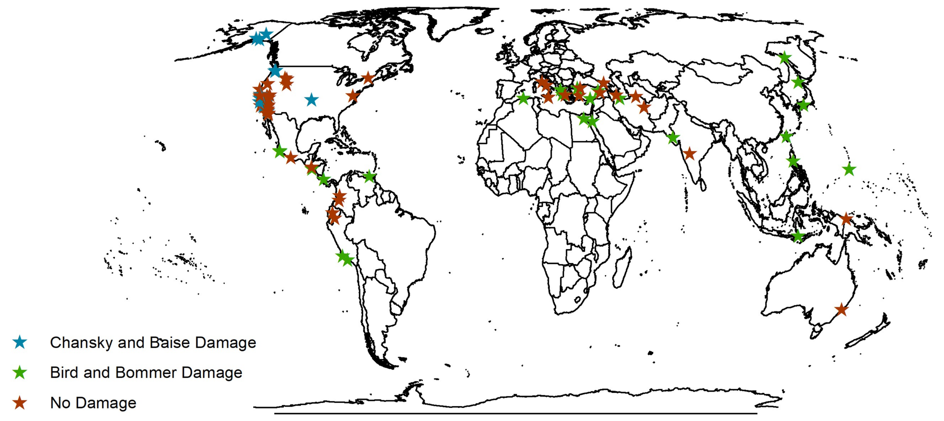


Figure 1: Locations of 12 earthquake epicenters across the United States which have calculated costs associated with them, 46 events only examined by Bird and Bommer (2004) without associated costs, and 28 events of no known liquefaction damage included for fragility function calculations later in this project.

Table 1: Breakdown of costs due to liquefaction, sorted by ascending *Htot* values, calculated in figure 2 caption. After the US project is complete, we hope to move onto international events. Cells under the "*Bird and Bommer, 2004*" header represent whether the earthquake was given a damage state of 0, 1, or 2, represented by the symbols "-", "X", and "XX". respectively. These damage states correspond to no liquefaction damage, minor/moderate liquefaction damage relative to the total earthquake damage, or major liquefaction damage relative to total event damage for each category. Green cells represent data added by this project, using categorization consistent with *Bird and Bommer (2004).* Cells under the "*Rashidian and Baise, 2020*" header use damage state categorizations consistent with *Rashidian and Baise (2020),* where green cells represent data added in this project. For the columns under "*Chansky and Baise, working*" header, non-highlighted cells represent values in the first quartile for that column while increasingly dark blue highlights represent values for the column in the second, third, and fourth quartiles for its column.

						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

HTOT AND POPULATION EXPOSURE CALCULATIONS

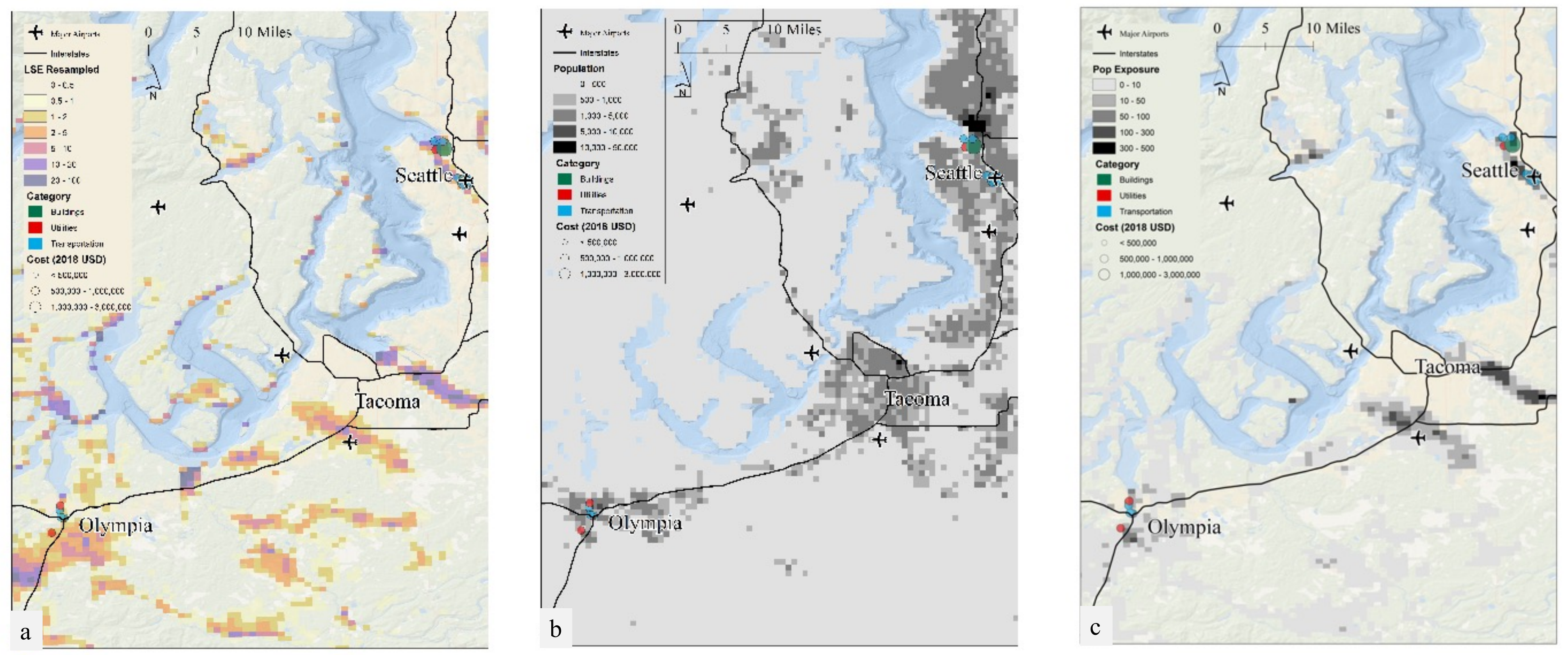
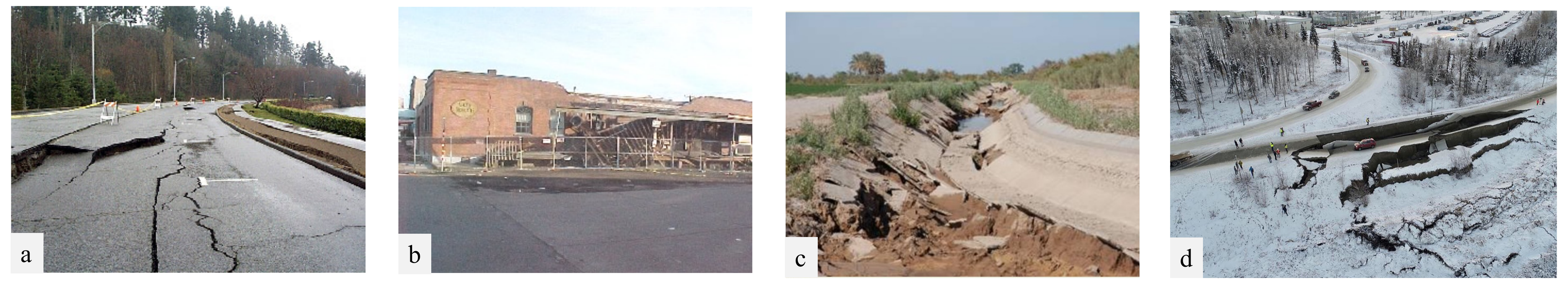


Figure 2. a: LSE Value for 2001 Nisqually event resampled to lower resolution matching LandScan 2016. **b**: Population density in Nisqually event's region obtained from LandScan 2016. **c**: Population exposure raster, calculated as the product of LSE and Population rasters. In the LSE raster, the summation of cell values multiplied by the area of each cell produces *aggregate liquefaction hazard* values for each event, or *Htot* as referred to by the USGS. The summation of cell values in the population exposure raster multiplied by the area of each cell produces *population exposure* values for each event, or *PopExp*. All maps include locations, cost range, and infrastructure category of 2001 Nisqually liquefaction damages.

LIQUEFACTION LOSS ACROSS INFRASTRUCTRURE



2001 Nisqually	2001 Nisqually	2010 Baja	2018 Anchorage
Transportation; Road 3	Building; Commercial	Utilities; Water	Transportation; Road 4
Damage to the Deschutes Parkway, Olympia	Damage to two adjoined brick buildings in Seattle	Liquefaction damage to agricultural irrigation canals	Road and embankment failure

Figure 3: Examples of damaging liquefaction occurrences across three US events. First row indicates year and location of event, second row indicates category and subcategory of each damage, and third row gives a brief description of the damage shown. Pictures and text obtained from GEER Association reconnaissance reports for each event.

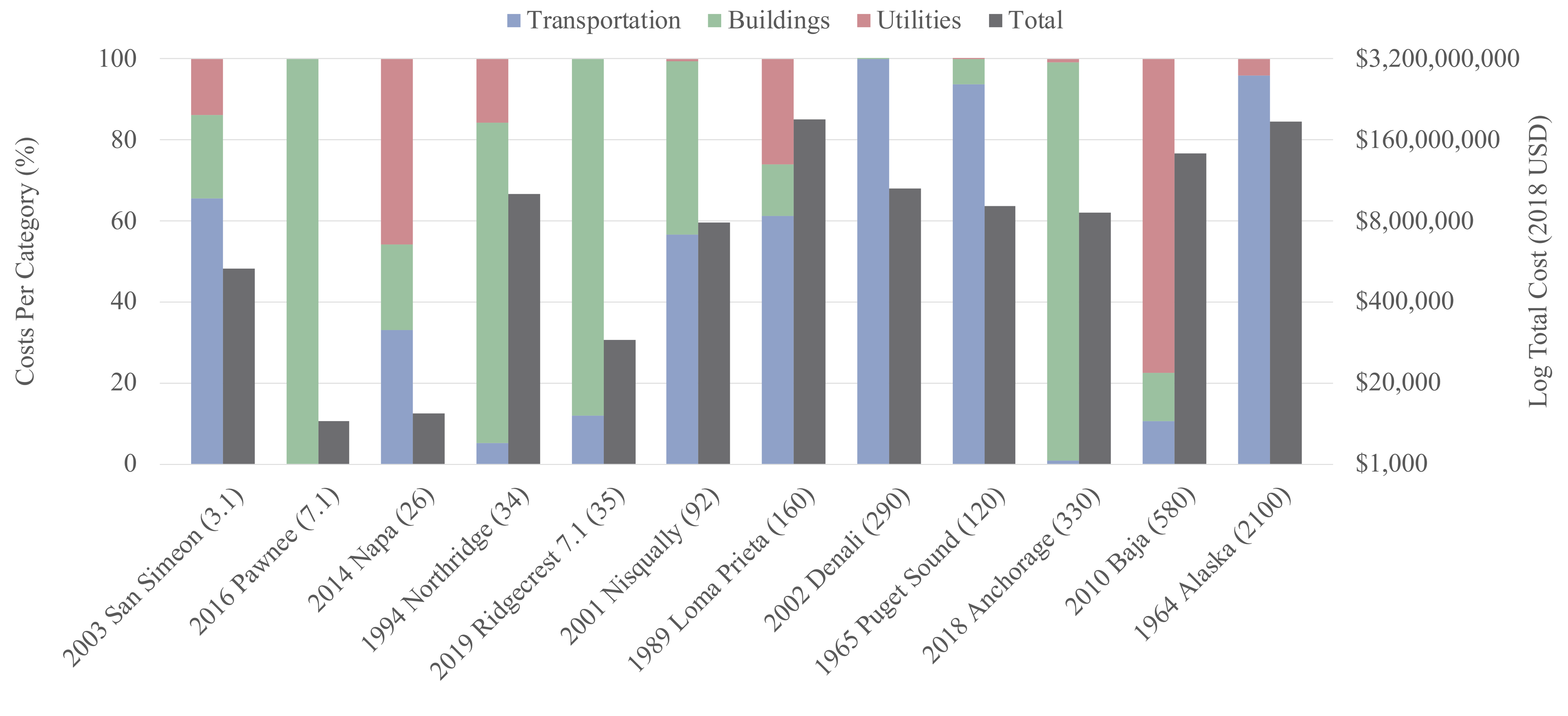


Figure 4: Percentages of the total costs by category and total cost for each event, sorted by ascending *Htot* values in parentheses. Bars on the left use the left axis and represent total cost percentage by category while bars on the right use the right axis represent total event's liquefaction cost. From this plot, damages categorized as transportation can be seen as the primary cost driver for most events. We also see that events in rural areas such as Baja and Anchorage have higher costs in categories other than transportation. In rural areas with less infrastructure, it is generally considered less likely that liquefaction will cause damage than in a densely populated area. More specifically, it will cause different damage depending on the pattern of infrastructure in the rural area. For example, the 2010 Baja event caused liquefaction primarily to agricultural canals and crops, categorized under utilities.

LIQUEFACTION LOSS VS. HTOT AND POPULATION EXPOSURE

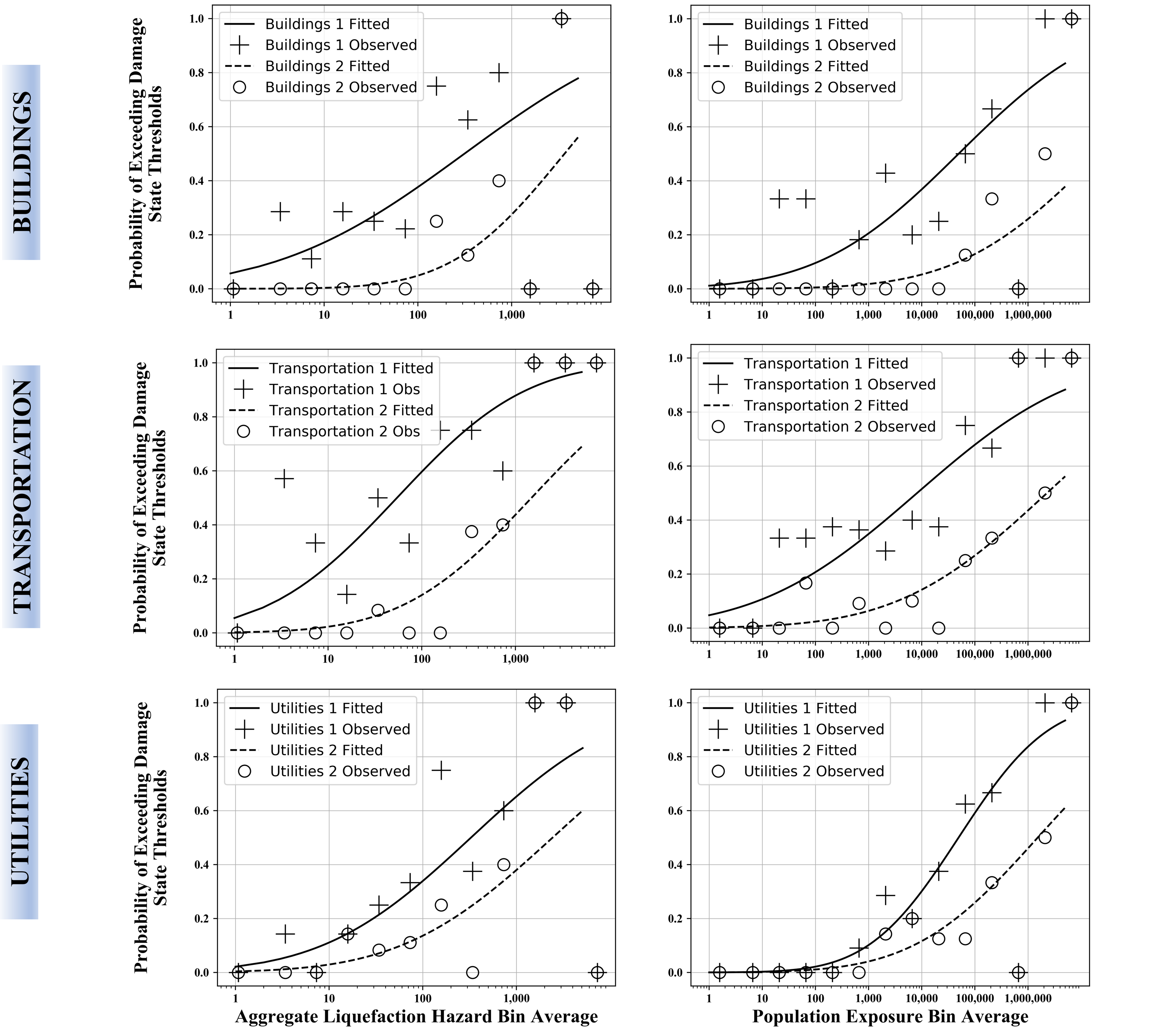


Figure 5: Fragility functions representing probabilities of exceeding damage state thresholds for different levels of excitation measures, calculated using empirical fragility functions and bounding-failure excitation method as described in *Porter (2021).* Figures in the left column use the excitation measure of aggregate liquefaction hazard (*Htot*) for each event while figures in the right column use the excitation measure of population exposure for each event. As expected, probabilities of exceeding damage state thresholds increase with increased excitation measure values in all categories. These figures include data from 12 events in this project's database, 46 events unique to the *Bird and Bommer (2004)* database, and 28 US events without liquefaction damage, for a total of 86 events. The events without liquefaction damage were assigned a damage state of 0 for all categories. These were included to reduce bias towards higher probabilities of damage for low excitation measure values.

ONGOING STEPS

- The project's next goal is to use damage states based on cost values to produce robust cost-based fragility functions for each category and total cost. An example of damage states based on total cost of each event is shown in figure 6.
- Different damage state dollar value cutoffs will be considered to determine the most appropriate values which show cutoffs of interest in the data without overwhelming users with too many curves and data points.
- We will also use different excitation measures such as population exposure, building exposure, or transportation network exposure and examine which results fit the data best.
- Uncertainty analysis will also be conducted to determine the reliability of these parameters being used on a national scale.

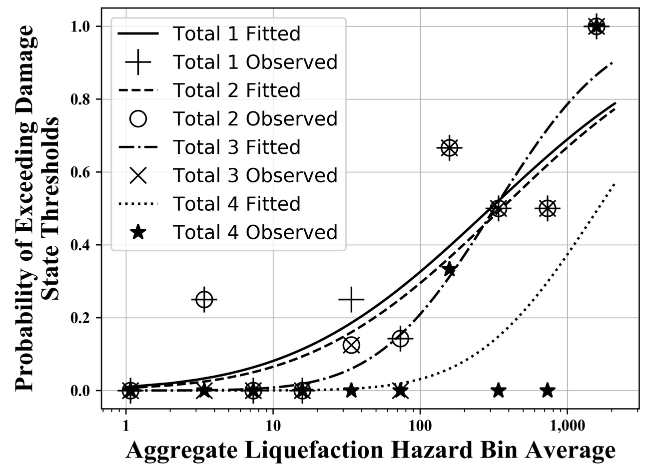


Figure 6: Fragility functions representing probabilities of exceeding damage state thresholds for aggregate liquefaction hazard. Damage states 1 through 4 represent exceeding dollar damage values of $10k, $1M, $10M, and $100M, respectively.

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